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AGARD LECTURE SERIES No.132

Operation and Performance Measurement on Engines in Sea Level Test Facilities

NORTH ATLANTIC TREATY ORGANIZATION

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NORTH ATLANTIC TREATY ORGANIZATION

ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

AGARD Lecture Series No.132

OPERATION AND PERFORMANCE MEASUREMENT ON ENGINES IN SEA LEVEL TEST FACILITIES

The material in this publication was assembled to support a Lecture Series under the sponsorship of the Propulsion and Energetics Panel and the Consultant and Exchange Programme of AGARD presented on 26–27 April 1984 in Rome, Italy; on 30 April–1 May in Ankara, Turkey and on 3–4 May in Athens, Greece.

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Published March 1984

ISBN 92-835-0350-3

Printed by Specialised Printing Services Limited
40 Chigwell Lane, Loughton, Essex IG10 3TZ

PREFACE

This Lecture Series considers all the basic features of turbojets and turbofan testing.

In the introduction, test cell design is set in historical perspective with brief descriptions of the test arrangement and instrumentation used to test the early jet engines. The way in which these have evolved to modern designs is outlined.

Three typical uses for sea-level test beds, routine proof-testing following overhaul, performance evaluation for type certification and general development testing are described and covered in detail by specialist lectures. One lecture is devoted specifically to turboprop testing.

Instrumentation and data handling are dealt with in two lectures, one covering measurement techniques and the other covering data acquisition and handling.

One lecture is devoted to the derivation of the performance of the engine from the test bed measurements.

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Operation and Performance Measurement on Engines in Sea-Level Test Facilities

Introduction and General Survey

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SUMMARY

Several aspects of sea-level testing are reviewed to provide an introduction and background to the seven specialist papers which make up this Lecture Series.

The review commences by setting cell design in historical perspective and considering the facilities that were used in the UK to test the early jet engines. A more modern cell, the 'Glen' Test House at Pyestock, is described in detail because its design contains all the basic features required for testing turbojets and turbofans. Attention is drawn to two areas where the original 'Glen' systems have been enhanced to meet modern requirements: the instrumentation and the method of measuring thrust.

Three typical uses for sea-level test beds, routine proof testing, performance evaluation and general development testing, are each briefly described and their influence on test bed design and instrumentation requirements discussed.

Instrumentation is considered only in outline because of its highly specialist nature, but attention is drawn to the need for the data output to be presented in easily assimilated form, particularly when processing is carried out on line.

Finally an account is given of an investigation made at Pyestock under the author's direction to examine the aerodynamic factors which influence thrust measurement. As published information on this topic is still extremely limited, and in view of its relevance to the present Lecture Series, the opportunity has been taken to make the results of these tests more widely available.

1.0 INTRODUCTION

In the early days of the turbine engine it was suggested that since the processes of compression, combustion and expansion take place in different components, each could be studied in isolation and there would be less need for testing the complete engine than was the case for piston engines. It was claimed that component test rigs could be more fully instrumented than complete engines and more detailed measurements taken over a wider range of operating conditions. However the argument ignored the difficulty of testing components under transient conditions (simulating rapid changes of power output) and it overlooked the influence of the interactions that occur between components.

Needless to say it was quickly realized that the argument could not be sustained and that full-scale engine testing had an essential role to play in aero-engine development. Component testing is equally necessary and the two perform complimentary functions in the process of establishing a firm data base from which a specific design is ultimately cleared for flight.

2.0 TEST CELL DESIGN - Historical perspective

2.1 The Early Test Cells

The facilities used to test the early jet engines were extremely simple and were constructed in existing buildings. In a lecture delivered in London before the Institution of Mechanical Engineers in October 1945 Air Commodore (later Sir Frank) Whittle described the set-up used to test his first experimental engine in April 1937. "For test purposes the engine was mounted on a four-wheeled trailer. This trailer also carried the starter motor, instrument panel and controls, making the whole set self-contained except for the fuel supply from the fuel tank and the water supply. It was intended to measure the thrust by a spring balance connecting the trailer to a fixed abutment, but in the testing of the first model no thrust measurements were taken"

Figure 1, reproduced from the lecture referred to above, is a photograph taken about 1939 of a similar arrangement with Whittle's third experimental engine installed. The 10 hp motor car engine which was used as a starter can be seen to the left of the picture with its radiator and fuel tank. Instrumentation was minimal and was mainly confined to measurements required to control the engine: shaft speed, oil and fuel pressures, jet pipe temperature, etc. All instruments were read 'by eye' and the operators were in close proximity to the engine. No attempt was made to silence either the intake or the exhaust.

2.2 Test Bay No 4 Pyestock

As the need for jet engine test facilities grew, purpose-built test cells were constructed. An example is Test Bay No 4 at Pyestock, shown in Figure 2, which was brought into use in 1946. It was built

to provide facilities for research on turbojet engines and was used for investigations on reheat combustion and on engine control systems. It is still in use although not for jet engine testing.

The cell was essentially an open-ended hangar with a separate sound-proofed control room which also housed the instrumentation. The engine was mounted on a frame suspended from the roof by four rods. These can be seen in Figure 3 which shows a Power Jet W2/700 engine installed for test. An interesting design feature was the use of a system of rods and cranks to couple the fuel control valves on the engine to the throttle lever in the control room. It is believed that this system was used because the flexible control cables available at the time were insufficiently reliable and did not give the required sensitivity of control. It is unlikely that it would be used today in view of the requirements for greater accuracy in thrust measurement.

The instrumentation installed in Test Bay No 4 reflected the standards of the time and used simple, direct-reading instruments. Pressures were measured with water or mercury manometers and Bourdon gauges, temperatures with thermocouples and resistance thermometers and fuel flow with variable-orifice and direct displacement meters. The test bed had in-built provision for measuring a maximum of 30 individual pressures and 85 individual temperatures.

2.3 'Glen' Test House Pyestock

The third generation of test cells is typified by the 'Glen' Test House at Pyestock which was commissioned in 1958 and is still in regular use. The general layout of the building is shown in Figure 5. The test cell is fully enclosed with built-in intake and exhaust silencing. It was designed around a hypothetical engine having an air flow of 115 kg/s and reheat to 2000°K. It was assumed that the ratio of induced cooling flow to engine flow would be in the region of 3:1, so that the total air flow entering the cell would be 460 kg/s. The intake silencing splitters were sized to pass this air flow at a velocity of 10 m/s.

The basic cell is 6.1 m high, 7.3 m wide and 17.7 m long. At its forward end a transition section leads to a chamber 10.7 m wide and 9.1 m high which houses the acoustic splitters. At the exhaust end a duct 3.0 m diameter connects with the detuner. The upstream end of this duct is fitted with a telescopic section which can be adjusted axially to match the position of the nozzle of the test engine.

Figures 6, 7 and 8 show respectively the intake splitters, the interior of the cell and a view from the control room with an engine running in full reheat.

The supports for the thrust frame are anchored to the floor of the cell and this results in the engine centre line being some 3.0 m above ground level. A permanent platform surrounds the engine to give convenient access.

The thrust measuring system and the engine support frame were designed for a maximum thrust of 125 kN with a limit on maximum engine diameter of 1.4 m. The engine frame is supported by sleeves sliding on three fixed bearings, two at the forward end and one at the rear. The axis of each bearing lies parallel to the line of action of the engine thrust. The weight of the engine and its support frame is transmitted to the sleeves through gymbal rings so that any slight misalignments can be accommodated. Oil is circulated continuously under pressure through the bearings to minimise friction.

A major virtue of this type of suspension is that it is a zero-rate system, that is there are no pendulum effects due to gravitation such as exist with suspensions using rods or flexures.

The original thrust measuring system used a mechanical linkage to transfer the thrust to two weighing machines located in the control room. One machine covered the range 0 to 65 kN and the other 60 to 125 kN. The system was calibrated by applying weights to a permanently installed calibrating arm located at the forward end of the test frame.

The basic design of the cell remains valid today, the only changes found necessary being to the instrumentation and the thrust measuring system. The original instrumentation has been replaced with a modern data acquisition, processing and recording system based on the use of transducers and a microprocessor. The mechanical thrust measuring system has been superceded by one using shear force load cells.

2.4 Modern Test Cell Design

The foregoing descriptions relate to facilities for testing turbojet or turbofan engines. The requirements for turboprops are rather difficult and for this reason they are normally tested in specifically dedicated cells. It is unusual for a test cell to be equipped for testing both turbojets and turboprops.

A turboprop engine needs to be coupled to a dynamometer to measure the shaft power output. It therefore has to be secured rigidly to the floor of the test cell and not mounted on a swinging frame as is the case when measuring the thrust of a jet engine. A rigid mounting enables the engine exhaust to be close coupled to the silencer with the result that the exhaust does not entrain a large ventilating air flow through the cell. This in turn reflects on the design of the air entry system since this has to handle an air flow only slightly in excess of that required by the engine.

The testing of turboprop engines is discussed in the Lecture by Hr Wunder.

Probably the most important feature of a jet engine test bed is an ability to measure thrust accurately. Ideally this requires the cell to represent free-field conditions, but since this cannot be achieved in practice steps have to be taken to ensure that the influence of the enclosing effects of the cell walls is kept to a minimum. The corrections that have to be applied to the measured frame reaction to allow for these interference effects are set out in Section 5.0

All modern turbojet test cells embody the basic features of the 'Glen' Test House - a silenced air

intake, a section in which the engine is installed, an exhaust collector/diffuser and an exhaust silencer. However, they differ in detailed design features such as the method of supporting the thrust frame and the layout of the air inlet system. The geometry of the air inlet is important since it influences the uniformity of flow to the engine. The layout may be determined by the space available or factors such as the need to provide quick and easy access for the engine transporter trolley, but wherever possible a straight-through inlet system is to be preferred.

The aerodynamic, thermodynamic and acoustic factors which have to be taken into account when designing a new cell are discussed in the Lecture by Prof Jacques.

3.0 SCOPE OF SEA-LEVEL TESTING

Sea-level testing embraces a wide variety of objectives, for example routine tests made as part of the function of a maintenance base, development tests by engine manufacturers to prove new or modified designs and research programmes to examine fundamental aspects of engine behaviour. Each of these functions is normally the responsibility of one specific organisation so that basically different types of test are rarely undertaken on the same test bed. For this reason the relative emphasis given to particular details of design will vary from bed to bed, depending on the use to which the cell is to be put.

To examine these influences more closely, three different kinds of test will be considered. These are:

i) routine proof testing of service engines following overhaul;

ii) overall performance evaluation for Type Certification purposes;

iii) development testing of new or modified designs.

Each of these tests imposes different requirements on the test bed. For example, routine performance testing, Item (i), requires above all an ability to install the engine, connect the instrumentation, run the test and obtain reliable data in the shortest possible time. This is necessary to ensure a steady flow of engines through the overhaul line. Instrumentation can be limited to that required to determine a few standard parameters and it is usually only necessary to run the engine up and down the power curve to confirm that the performance lies within specified limits. The test is essentially a quality control exercise.

The use of sea-level beds for routine testing is described in the Lecture by Wg Cdr Rowlands.

Performance certification tests, Item (ii), usually require considerable instrumentation but the need to complete the test in a short time takes second place to achieving a high level of accuracy. With this type of test it is desirable to plan the programme in such a way that a provisional analysis of at least some of the data can be made before the engine is removed from the test bed. Repeat tests can then be run if required to check unexpected results and rogue data points.

The Lecture by Mr Rudnitski deals with performance testing and analysis of the results.

Development testing, Item (iii), is far more varied and covers a wider field than either of the two previous items. During the evolution of a new engine, bench tests have to be made to confirm that the engine operates satisfactorily and check the extent to which the assumptions made in the design have been realized. Any shortfalls in performance or unacceptable behaviour such as inadequate surge margin, excessive blade vibration, sluggish throttle response, etc, have to be investigated and their causes discovered. Solutions have then to be tested and their effectiveness assessed. In this situation it is inevitable that testing proceeds to a great extent on an ad hoc basis.

To be fully effective an engine development programme needs to be supported by a complimentary programme of component testing using specialist rigs. The two programmes together provide the data base required to clear the design for use in flight.

Development testing on engines and component test rigs is described in the Lecture by Mr Beanland.

4.0 INSTRUMENTATION AND DATA HANDLING

4.1 Aspects of System Design

The revolution in data acquisition and processing methods which has taken place over the past two decades and the development of miniature sensors and transducers has made it possible to undertake test measurements of a complexity and scale that would formerly have been impossible. It is not proposed to enter into detailed discussion of these developments as they are dealt with in the Lectures by Mr Bogia, but some general points will be presented.

Just as the emphasis given to specific design features of the test bed depends on the type of testing to be carried out, so it is with the data acquisition and processing system. For example, the requirement may be limited to steady-state testing or it may extend to include transient (ie time-variant) testing. In routine pass-off testing it is usually sufficient to measure only shaft speeds, fuel flow, thrust, jet pipe temperature, air inlet temperature and a few miscellaneous pressures and temperatures. Development and research testing on the other hand demand more detailed measurements and it is not unknown for a test to require the recording of several hundred individual pressures and temperatures. With data being accumulated on this scale it is essential for the output to be presented in a form that can be easily assimilated. The extent to which this can be done will depend on the computing power available. At the basic level of simplicity is the data logger which merely records the data in digital form on paper tape for subsequent off-line analysis using a separate computing facility. At the other extreme is the real time (on-line) system which acquires, processes and presents the data while the test in in progress. If the computer has sufficient storage capacity it can be programmed to display comparisions between the test in progress and

predicted data or with data from previous tests. Numerical tabulations are usually output as a matter of routine so that a more detailed analysis can be made if required. Hard copy can be obtained from the monitor screen display (VDU) or from a plotter and these can be filed for reference or even used directly in reports.

4.2 Notes on Pressure Measurement

Steady-state pressures can be measured either by using individual transducers, one for each pressure, or by connecting a number of pressure lines in sequence to a single transducer through a rotary pressure switch (Scanivalve). Neither system can be claimed to be wholly superior to the other. Individual transducers can be more closely matched to the range of pressures to be measured and the sampling rate is high (in the region 80-90 samples per second). However the calibration cannot easily be checked during a test and drift may occur if the transducer is temperature sensitive and its environment is not controlled to sufficiently fine limits. Pressure switching on the other hand can incorporate standard pressures to provide on-line calibration, but the sampling rate is low (typically 20-25 seconds to scan 42 pressures). Also the transducer has to be chosen to cover the total range of pressures being measured and this can mean that for some it will be operating near the low end of its range with consequent loss of accuracy.

Transducers used for measuring transient pressures have to be located as close as possible to the point of measurement. This usually means mounting them on or close to the engine in a relatively hostile environment. They are calibrated against the steady-state system both before and after the transient.

Transient data have traditionally been recorded on light-sensitive paper using multi-channel mirror galvanometers. Quantitative analysis of these records is a tedious and time consuming process involving the preparation of calibrated scales and reading off the required parameters. To avoid this a computerised digital system has been developed at RAE (Pyestock) and this enables the variation of selected engine parameters in real time to be observed directly on a VDU. Conversion of the data to digital form greatly simplifies its processing and assessment.

5.0 EXPERIMENTAL INVESTIGATION OF THRUST MEASUREMENT ERRORS

When testing in an enclosed sea-level test bed, the ejector action of the jet stream from the engine exhaust as it enters the exhaust collector (detuner) induces a flow of secondary air through the cell. This secondary flow gives rise to aerodynamic effects which cause forces to act on the thrust frame which, if not allowed for, give rise to errors in the measurement of thrust. The three main effects are:

i) a force on the inlet bellmouth due to the air entering it predominantly from the forward direction;

ii) a force on the nozzle due to the reduced external static pressure caused by the increased velocity of the secondary air as it approaches the exhaust collector;

iii) a drag force on the framework supporting the engine due to the secondary air flowing over it.

An investigation to determine the magnitude of these effects was undertaken a few years ago at Pyestock by Sqn Ldr (now Air Cdre) K A Campbell RAF. A report on the tests was issued at the time but unfortunately all the original measurements have since been discarded. The following summary is based on the report.

5.1 Instrumentation

The engine used for the investigation was a two-shaft reheated turbojet. All tests were made in the non-reheat mode. A conventional intake flare was attached to the compressor inlet. The flare was fitted with 27 static pressure tappings, 22 on the front face spaced around from the lip to the parallel section and 5 on the rear face extending over a short distance from the lip.

The jet pipe terminated in a variable-area convergent nozzle and was surrounded by a fixed shroud. This formed an annulus through which cooling air flowed. The downstream end of the shroud converged and extended approximately half a nozzle diameter beyond the nozzle exit plane.

Static pressures were measured on the outside and inside surfaces of the convergent portion of the shroud and on the outer surface of the nozzle. The static pressure at the shroud exit plane was measured using a piezo ring.

5.2 The Test Programme

The tests were run in the 'Glen' Test House with the exhaust collector set at different distances from the engine nozzle. In what follows the ratio nozzle diameter/collector gap will be referred to as the gap ratio. The gap ratio is thus inversely proportional to the distance between the exit plane of the nozzle and the entry plane of the collector. This form was chosen because over the range of conditions tested it was found that at a given engine speed the depression at the nozzle exit was directly proportional to the gap ratio. (Section 5.3.2).

At each gap ratio measurements were made of the static pressures on the intake flare and on the convergent surfaces of the nozzle and shroud. Data were obtained at five engine speeds covering the upper end of the range. Gap ratios of 0.37, 0.56, 0.70 and 1.59 were used. Repeat tests were made with gap ratios of 0.70 and 1.59.

Approximately half the collector cross-section was then blanked off to reduce the entrainment ratio. Tests were made with gap ratios of 0.37, 0.70, 1.07 and 1.59.

5.3 Analysis of Results

5.3.1 Thrust Coefficient

Figure 9 shows the thrust coefficient, C_x, for all the tests in the series. The thrust coefficient is defined as the ratio of measured gross thrust to the thrust calculated assuming isentropic expansion at the same nozzle pressure ratio.

It is clear that C_x increases as the gap ratio is reduced, that is as the distance between the nozzle and the collector increases. C_x also increases with collector blockage, that is as the entrained air flow is reduced.

Figure 9 also shows that with no blockage the two tests with the 1.59 gap ratio fall on two distinct lines and the three with the 0.70 gap ratio fall on three lines. As all the tests were conducted in an identical manner it was clear that a day to day variation in C_x existed. After condsiderable investigation the cause was found to be the direction and strength of the wind outside the cell. The test at 1.59 gap ratio which gave the higher values of C_x was conducted in a flat calm, whilst a wind of 3 m/s was blowing directly into the cell intake during the second test at this gap ratio. A similar effect was thought to occur on the days when the tests were made with a gap ratio of 0.70.

5.3.2 Nozzle Static Pressure Correction

The static pressures measured on the shroud and nozzle were used to derive the mean pressure at the nozzle exit. The difference between this and the cell pressure is shown in Figure 10 plotted against the gap ratio for $N_L/\ T_1$ 400. It will be seen that as the gap ratio decreases the nozzle pressure approaches the cell static pressure.

5.3.3 Intake Flare Correction

A theoretical treatment of the influence of the cell walls on the intake flare force is given in Appendix I. This shows that there is an inlet momentum effect due to the ventilating air flow of magnitude $(Q_1 V_0)$ .f(E) where Q_1 is the engine air flow, V_0 the velocity of the air approaching the flare and f(E)=(2E+1)/2(E+1) where E is the ratio of ventilating flow to engine flow.

This represents a drag force on the test frame and is analoguous to an inlet momentum effect in flight. The flare force obtained from the measured static pressure distribution was compared with that calculated using the above formula and fairly good agreement obtained, although with some scatter, particularly for the tests with no exhaust collector blockage. The scatter was thought to be due to errors in the determination of mean cell velocity which proved to be a difficult quantity to measure. After several trials with different instrumentation, anemometers were used but there was an appreciable fluctuation in their readings and this made if difficult to obtain reliable mean values.

5.3.4 Test Frame Drag

The drag of the test frame reduces the measured frame reaction by an amount equal to the drag force. In the 'Glen' Test House the test frame consists mainly of I-girders. An estimate was made of the total projected area in a plane normal to the ventilating air flow and the drag calculated assuming a drag coefficient of 1.5.

When testing with the smallest collector gap the rear beam of the test frame came very close to the mouth of the collector. As a result it was immersed in a fairly high velocity airstream and this could have produced a significant drag. No attempt was made to estimate this and it has not been considered in the results.

5.3.5 Corrected Results

Figure 11 shows the thrust coefficients corrected to allow for the three effects described above. It will be seen that the results fall much more closely about a mean curve than do the uncorrected results given in Figure 9. However they still exhibit a scatter of ± 1 per cent at low speeds and ± 0.5 per cent at maximum speed. This results with the smallest collector gap (Test Points 3 and 4) are outside this scatter, but this was thought to be due to the drag on the rear beam of the thrust frame mentioned in Section 5.3.4.

Estimates of the effect on C_x of likely errors in the measurement of thrust, ventilating air velocity and thrust frame drag give figures of ± 0.3 per cent at maximum speed and ± 0.7 per cent at lower speeds. The results shown in Figure 11 are therefore approaching the limits of resolution of the cell instrumentation.

6.0 CONCLUSIONS

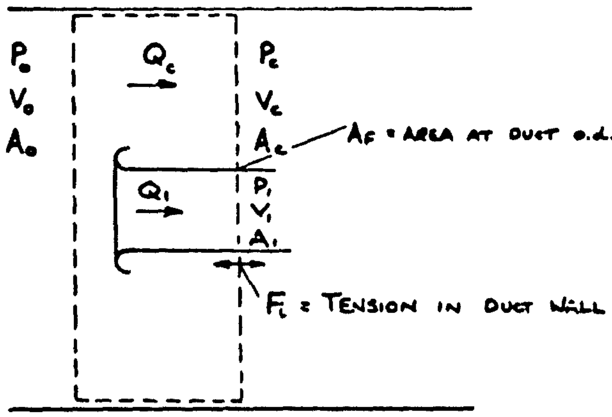
Some aspects of sea-level testing have been reviewed to provide a background to the specialist papers which make up the Lecture Series. Specific features of test cell design have been described, requirements arising from different types of tests discussed and attention drawn to the potential offered by modern data acquisition and processing methods. The Paper concludes with a description of an experimental investigation made under the author's direction to examine the aerodynamic factors which influence thrust measurement.

ACKNOWLEDGEMENT

The author wishes to thank the Procurement Executive of the Ministry of Defence for permission to draw on information contained in Official Reports. The views expressed are entirely the author's own. Figures 1-8 are copyright Controller HMSO London.

APPENDIX I

Analysis of Intake Flare Force



Assumptions:

(i) Parallel sides to momentum box along wall of test cell between planes "0" and "C".

(ii) Skin friction neglected on cell walls.

(iii) Uniform static pressure and velocity in planes "0" and "C".

(iv) Isentropic flow between planes "0" and "C" (ie outside the intake but inside the box).

Theory:

The net force acting on the intake within the momentum box is equal to the difference between the momentum leaving the box in unit time and the momentum entering the box in unit time. Thus:-

$$P_0 A_0 - P_c (A_0 - A_F) - P_1 A_1 + F_i = Q_c V_c + Q_1 V_1 - (Q_1 + Q_c) V_0 \quad \ldots (1)$$

$$\therefore \; F_i = Q_c V_c + Q_1 V_1 - Q_1 V_0 - Q_c V_0 + P_1 A_1 - P_0 A_0 - P_c A_0 - P_c A_F$$

$$= \left[Q_1 V_1 + P_1 A_1 \right] - P_c A_F + Q_c (V_c - V_c) - Q_1 V_0 + (P_c - P_0) A_0 \quad \ldots (2)$$

To eliminate Q_c, V_0 and V_c in favour of Q_1 and E we use:-

$$Q_c = E Q_1$$

$$\begin{aligned} \rho_0 V_0 A_0 &= Q_0 \\ &= Q_1 + Q_c \\ &= Q_1 (1 + E) \\ &= \frac{Q_c}{E}(1 + E) \\ &= \rho_c V_c A_c (1 + E)/E \end{aligned}$$

$$\therefore \; V_0 = \frac{Q_1}{\rho_c A_0}(1 + E) \quad \ldots (3)$$

$$V_c = \frac{Q_1}{\rho_c A_c} E \quad \ldots (4)$$

Hence we have for the third and fourth terms in (2):-

$$Q_c(V_c - V_o) - Q_1 V_o = Q_c V_c - V_o(Q_c + Q_1)$$

$$= EQ_1 \cdot \frac{EQ_1}{\rho_c A_c} - \frac{Q_1}{\rho_o A_o}(1+E)\, Q_1(1+E)$$

$$= \frac{Q_1^2}{\rho_o A_o}\left[E^2 \frac{\rho_o A_o}{\rho_c A_c} - (1+E)^2\right]$$

$$\doteqdot -\frac{Q_1^2}{\rho_o A_o}(1+2E) \qquad \ldots (5)$$

To eliminate the fifth term in (2) in favour of Q_1 and E we assume isentropic flow between planes "O" and "C"

$$P_o + \tfrac{1}{2}\rho_c V_o^2 = P_c + \tfrac{1}{2}\rho_c V_c^2$$

$$\therefore (P_c - P_o)A_o = \frac{A_o}{2}\left[\rho_o V_o^2 - \rho_c V_c^2\right]$$

Substituting for V_o, V_c

$$(P_c - P_o)A_o = \frac{A_o}{2}\left[\rho_o\left(\frac{Q_1(1+E)}{\rho_o A_o}\right)^2 - \rho_c\left(\frac{Q_1 E}{\rho_c A_c}\right)^2\right]$$

$$= \frac{Q_1^2}{2A_o}\left[\frac{(1+E)^2}{\rho_o} - \left(\frac{A_o}{A_c}\right)^2 \frac{E^2}{\rho_c}\right]$$

$$= \frac{Q_1^2}{2\rho_o A_o}\left[1 + 2E + E^2 - \left(\frac{A_o}{A_c}\right)^2 \frac{\rho_o}{\rho_c} E^2\right]$$

$$\doteqdot \frac{Q_1^2}{\rho_o A_o}\left[\frac{1+2E}{2}\right] \qquad \ldots (6)$$

Finally, substitute from (5) and (6) into (2):-

$$F_i = \left[Q_1 V_1 + P_1 A_1\right] - P_c A_F - \frac{Q_1^2}{\rho_o A_o}(1+2E) + \frac{Q_1^2}{\rho_o A_o}\left(\frac{1+2E}{2}\right)$$

$$= \left[Q_1 V_1 + P_1 A_1\right] - P_c A_F - \frac{Q_1^2}{\rho_o A_o}\left(\frac{1+2E}{2}\right) \qquad \ldots (7)$$

In free-field conditions with the flow not constrained by the cell walls, E=-½. The last term in (7) then becomes zero, giving the free-field intake flare force:-

$$F_{i_\infty} = \left[Q_1 V_1 + P_1 A_1\right] - P_c A_F \qquad \ldots (8)$$

The additional drag force on the intake flare is the difference between (8) and (7). Thus:-

Air Entrainment Force $= F_{i_\infty} - F_i$

$$= \frac{Q_1^2}{\rho_0 A_0}\left(\frac{1+2E}{2}\right) \qquad \ldots (9)$$

As an example of the magnitude of the intake flare force, a test in the 'Glen' Test House gave a measured thrust frame reaction of 16963 lbf with an engine air flow, Q_1 = 276 lb/s. The cross-section of the cell, A_o, is 480 sq ft, so substituting in (9) for Standard Day conditions gives:-

$$\text{Air Entrainment Force} = \frac{276^2}{32.2 \times 0.0765 \times 480}(\tfrac{1}{2} + E)$$

$$64.42\ (\tfrac{1}{2}+E)$$

The influence of Entrainment Ratio on the Air Entrainment Force, expressed in absolute terms and as a percentage of the thrust frame reaction, is shown in the following Table:-

E	AEF (lbf)	$(AEF/F_R) \times 100$
1	96.63	0.57
2	161.1	0.95
3	225.5	1.33
4	289.9	1.71

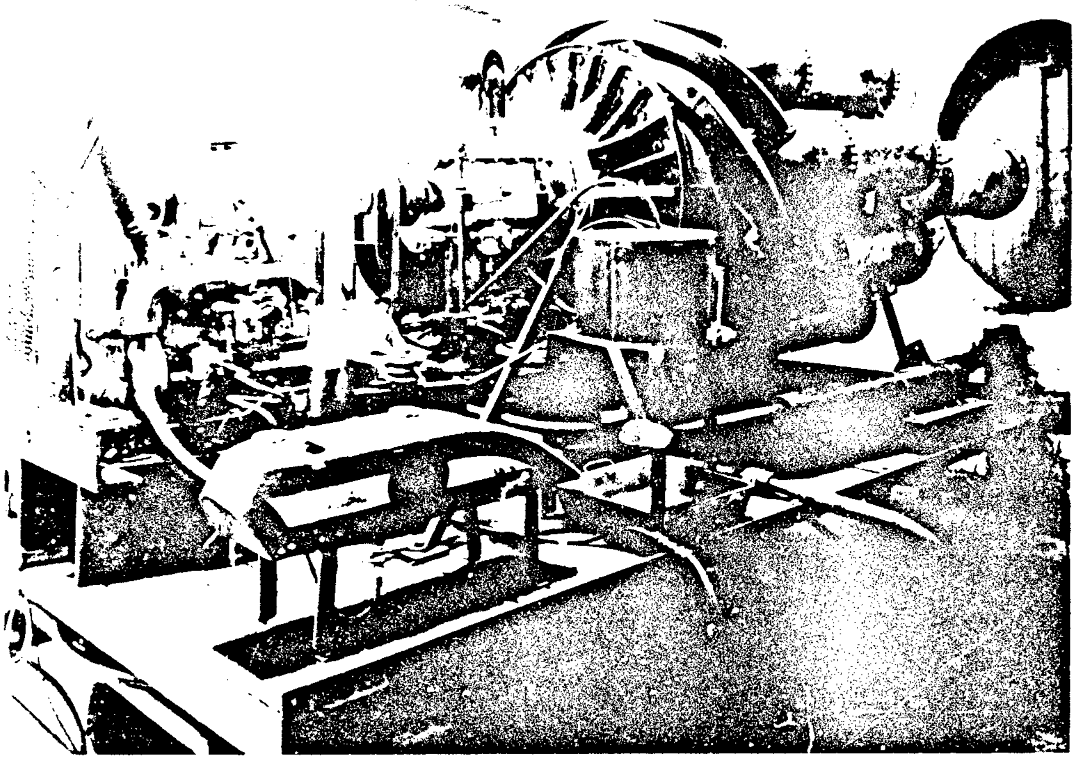


Figure 1 TEST INSTALLATION OF THIRD MODEL OF WHITTLE'S EXPERIMENTAL ENGINE (1939)

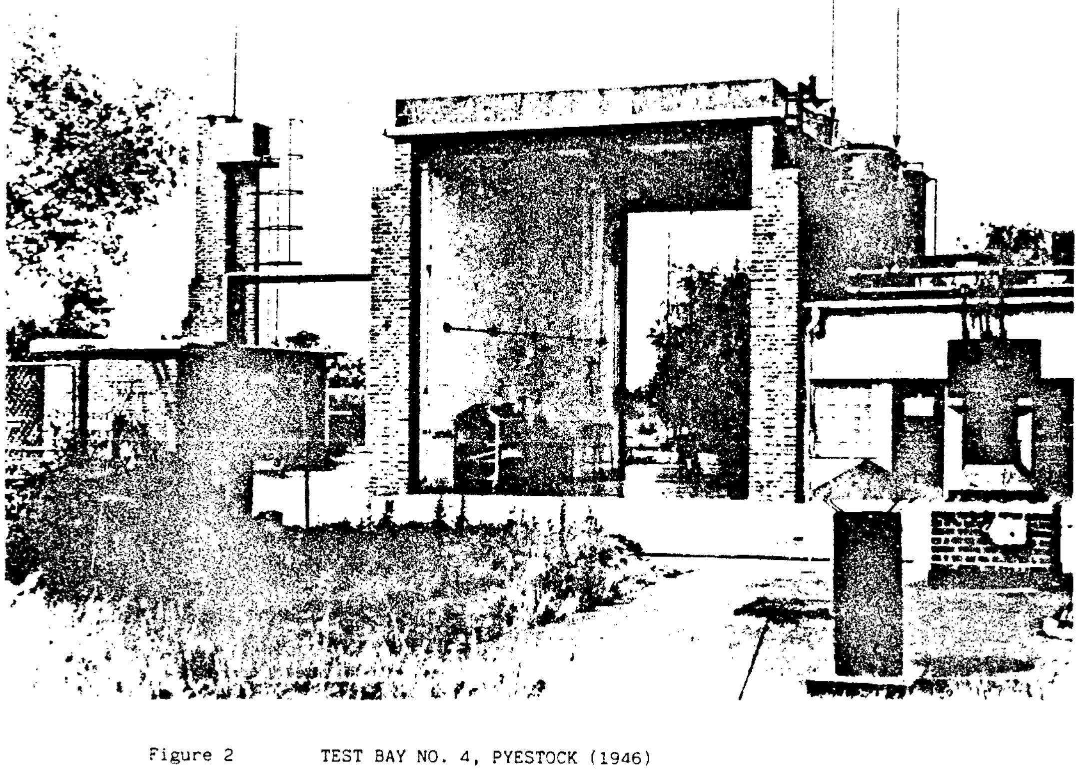


Figure 2 TEST BAY NO. 4, PYESTOCK (1946)

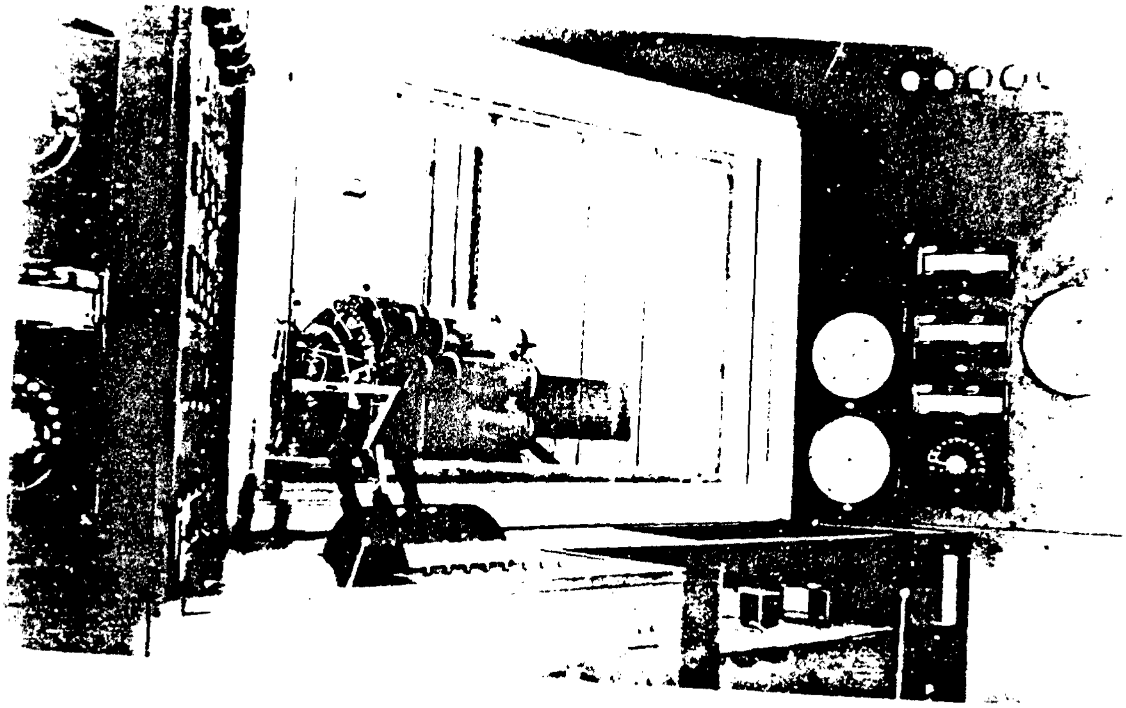


Figure 3 CONTROL ROOM OF TEST BAY NO. 4

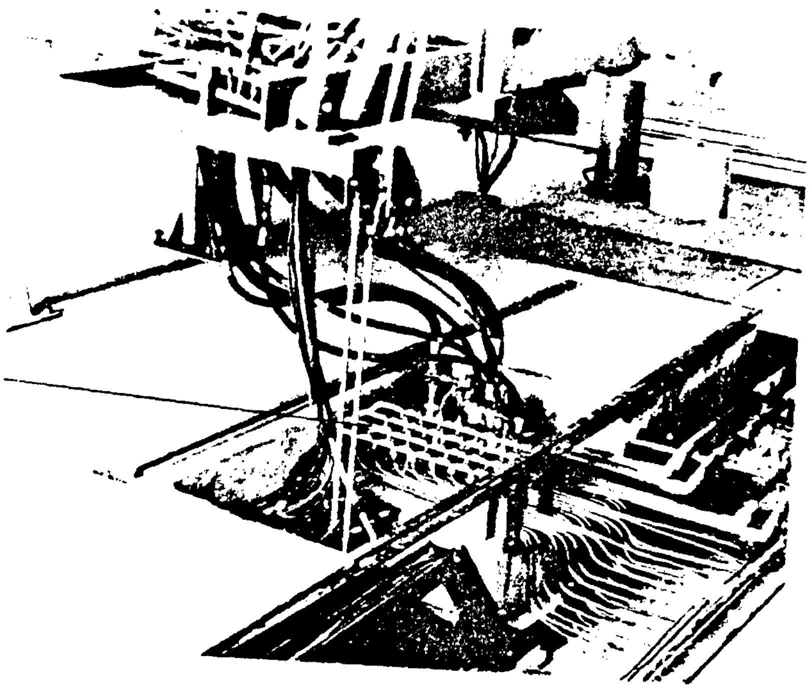


Figure 4 ENGINE CONTROL LINKS - TEST BAY NO. 4

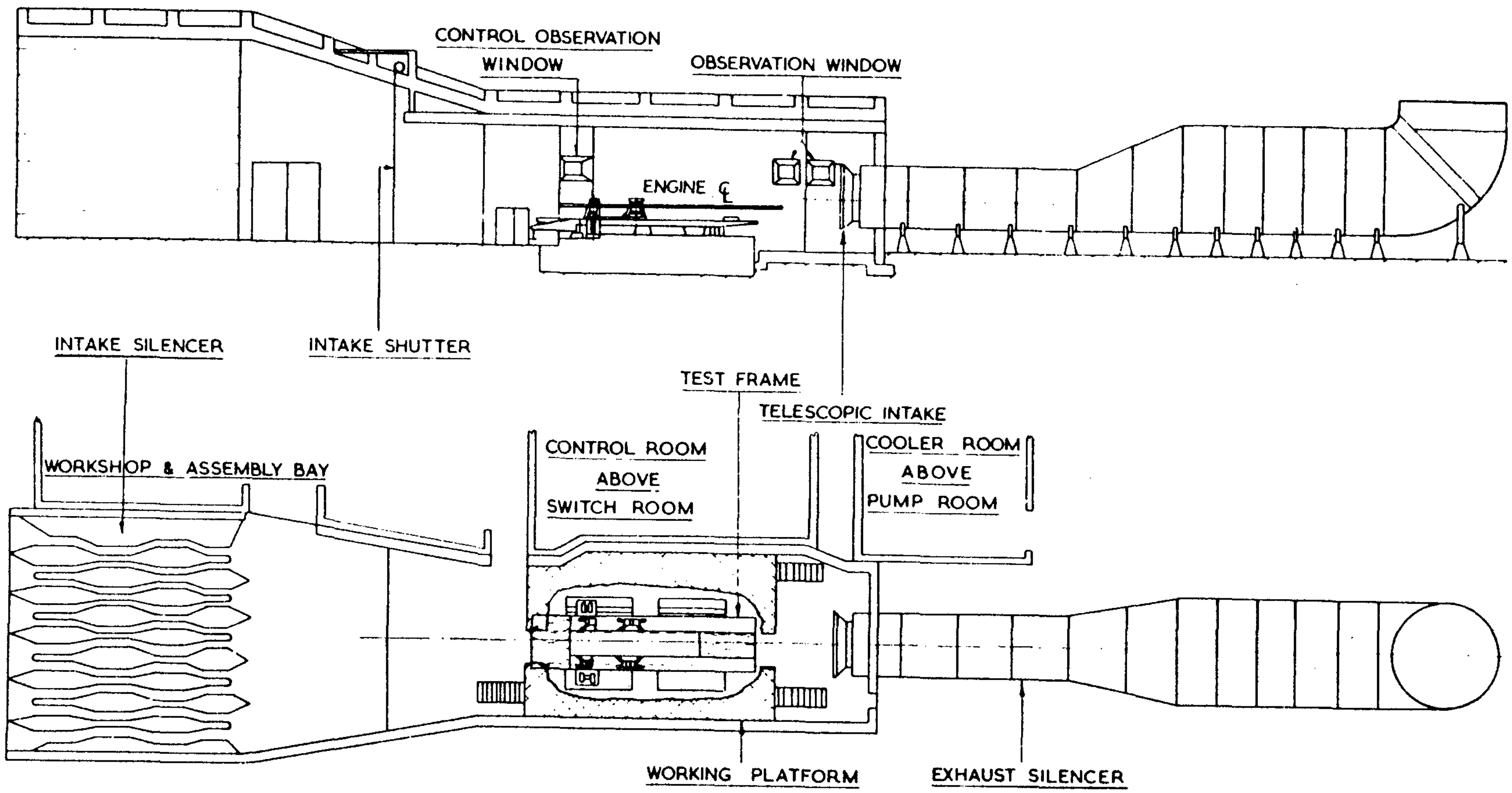


Figure 5 'GLEN' TEST HOUSE - GENERAL ARRANGEMENT

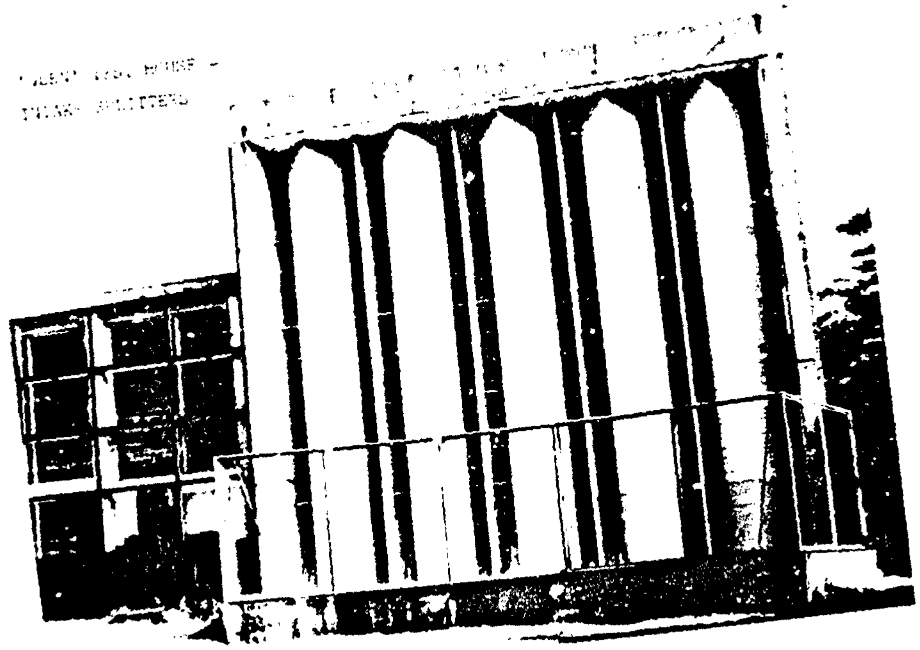


Figure 6 'GLEN' TEST HOUSE -
INTAKE SPLITTERS

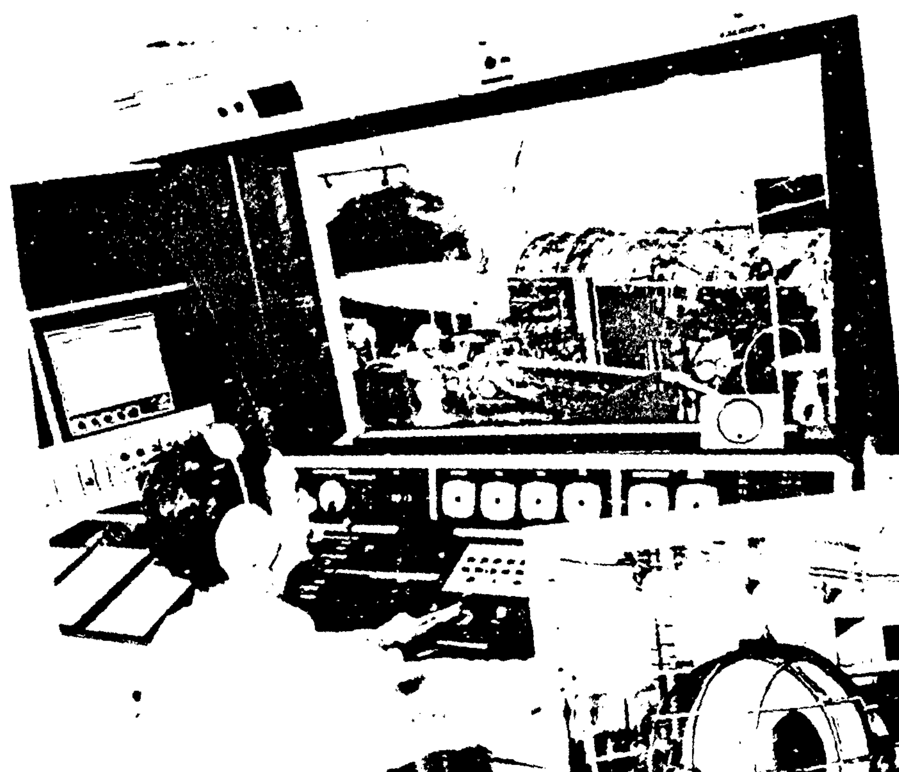


Figure 8 'GLEN' TEST HOUSE -
VIEW FROM CONTROL ROOM

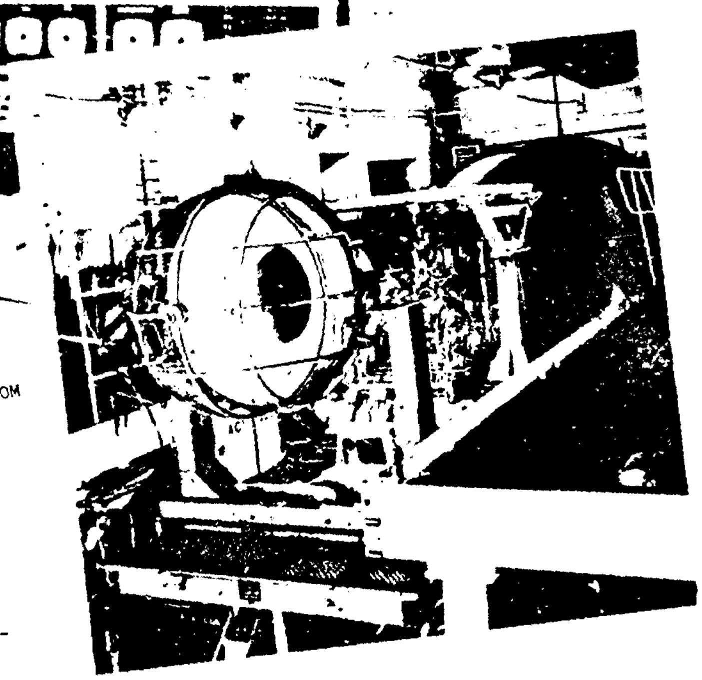


Figure 7 'GLEN' TEST HOUSE -
INTERIOR OF CELL

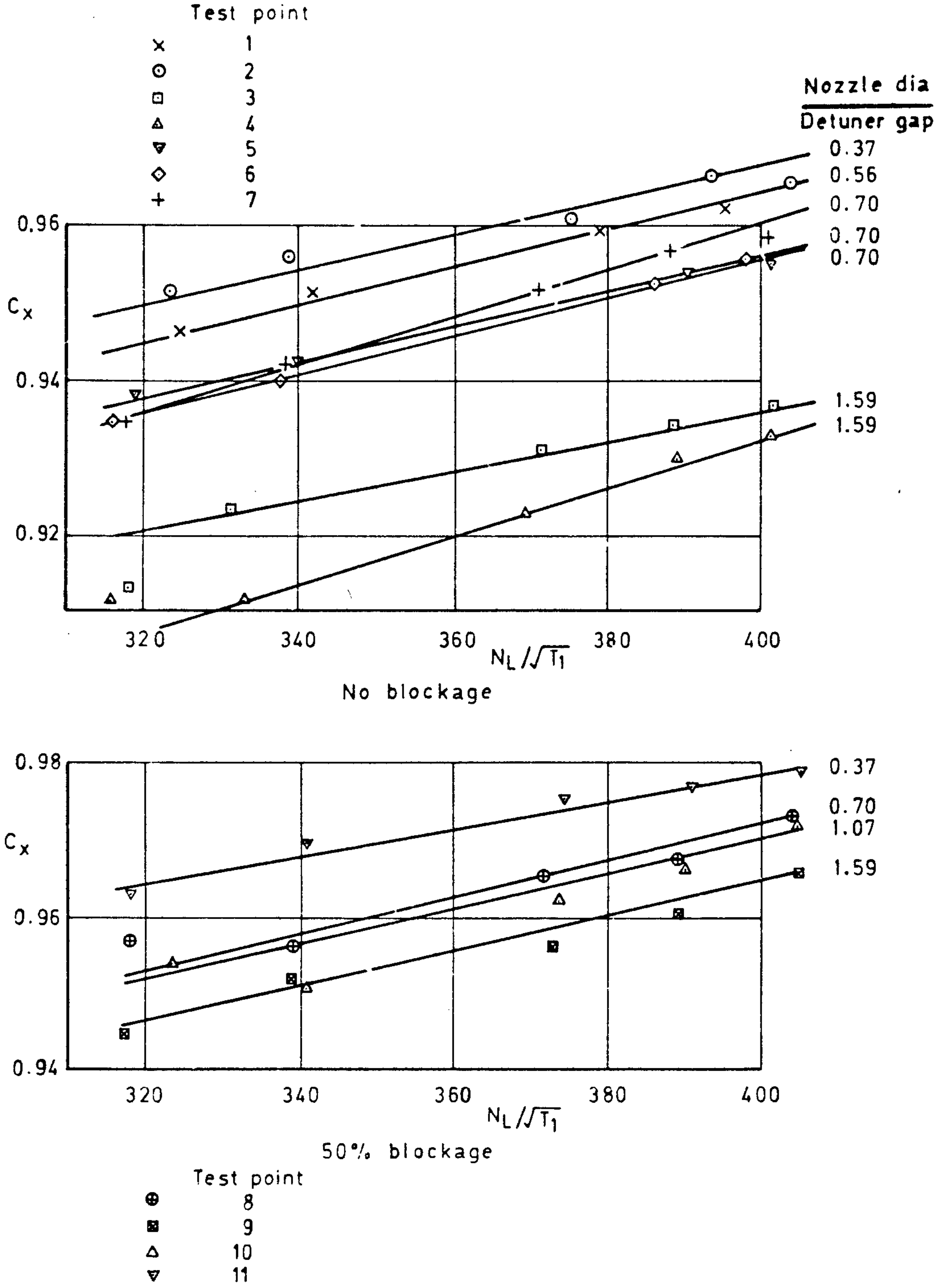


Fig 9 Variation of thrust coefficient with speed

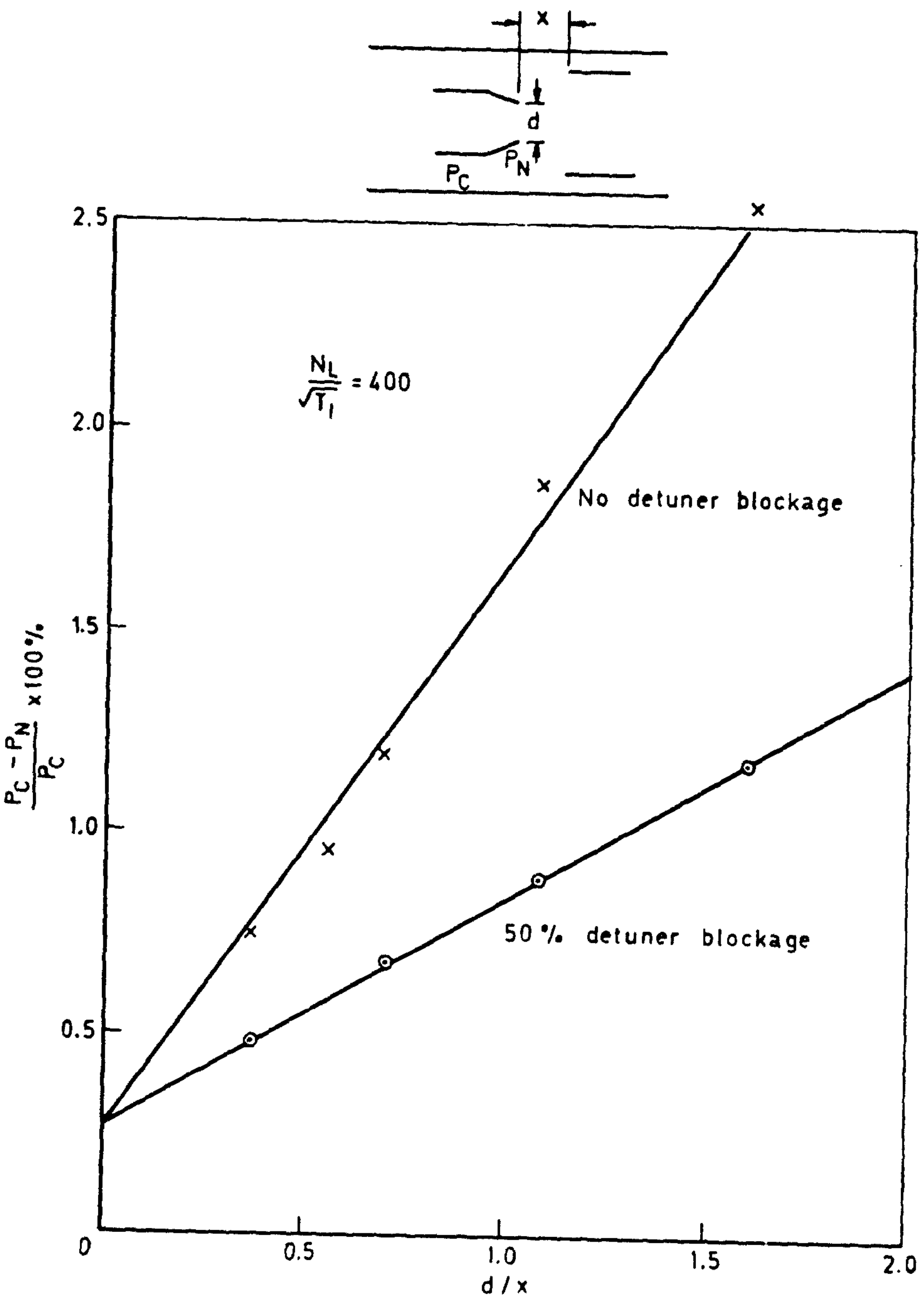
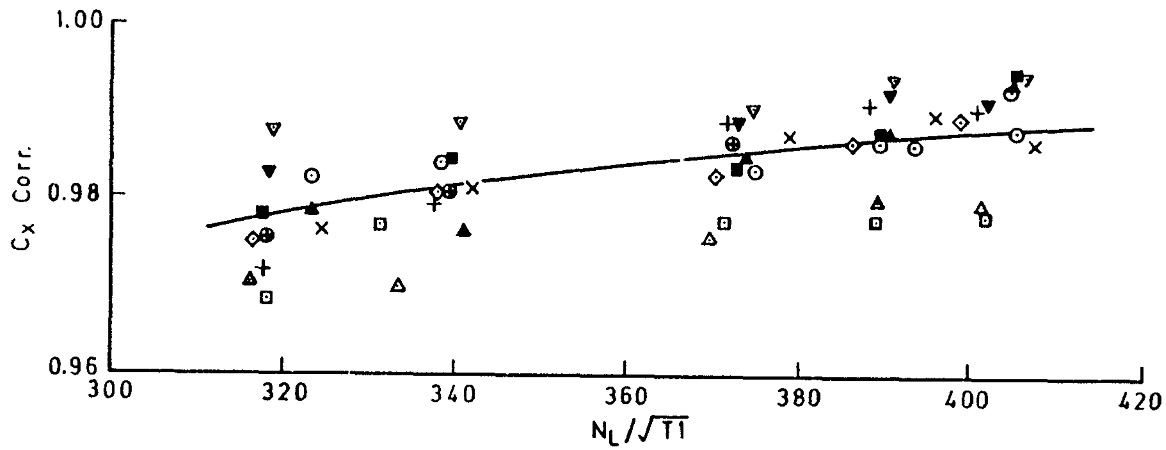


Fig 10 Effect of detuner gap on nozzle depression



	Test point	Nozzle dia / Detuner gap
×	1	0.56
⊙	2	0.37
⊡	3	1.59
△	4	1.59
▽	5	0.70
◇	6	0.70
+	7	0.70
⊕	8	0.70
■	9	1.59
▲	10	1.07
▼	11	0.37

Fig 11 Variation of corrected thrust coefficient with speed

AERO/ THERMODYNAMIC AND ACOUSTIC CONSIDERATIONS IN THE DESIGN OF TEST-BEDS FOR TURBOJETS AND TURBOFANS.

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SUMMARY.

The testing of non-installed engines or trimming of engines installed on aircraft has to be performed in closed test-beds on most of the airfields. The lecture starts with a general presentation of the closed test-bed and the lay-out of the buildings.

The thermodynamic equations for the calculation of the air and waterflows needed for the cooling of the hot gases ejected by the turbojet are established. These flows are a function of the thermodynamic performance parameters of the engine, and the maximum value of the temperature allowed by the materials used in the exhaust.

Correct measurement of the thrust imposes restrictions on the aerodynamics of the flow such as speeds and depression in the test-room. The required air flow enables us to determine the cross-section of the test-room. The choice of a test-bed with one or two air intakes depends on the airflows.

The aerodynamic equations must be established in order to calculate approximately the airflows through the test-bed. The airflows are functions of the cross-sectional areas of intake and exhaust stacks, ejector, flow loss coefficients and such engine parameters as thrust, temperatures and airflow.

Noise reduction in the surrounding environment is the first aim of the test-bed designer. The allowable noise level imposed by the user depends on the location and the orientation of the test-cell, and the distances from residential buildings, offices or workshops. We must start from the criteria prescribed by noise regulations. Taking into account the attenuation of sound with distance, the allowable noise level at a reference distance from the test-bed can be calculated. The engineer needs this figure to design the required noise insulation, thus the walls and the acoustic panels in air intakes and exhaust stacks. He must keep in mind the aero- and the thermodynamic requirements already mentioned.

These various aspects of the design of test-beds are illustrated by technical data and the results obtained in existing facilities.

CONCEPTION DES BANCS D'ESSAIS DE TURBOREACTEURS. ASPECTS THERMODYNAMIQUES, AERODYNAMIQUES ET ACOUSTIQUES.

RESUME.

Le cours débute par une présentation générale du banc d'essais de turboréacteurs de type fermé et du bâtiment destiné à la mise au point du moteur installé sur avion. Le coût de la construction sera influencé par la disposition des bâtiments sur le terrain. Ils peuvent être séparés ou groupés en fonction des besoins tactiques et techniques.

Les débits d'air et d'eau nécessaires au refroidissement des gaz éjectés par le réacteur sont calculés à partir des équations thermodynamiques. Ces calculs sont basés sur les performances du moteur et la valeur maximale admissible de la température des gaz à l'échappement du banc d'essai.

Une mesure correcte de la poussée impose des restrictions aérodynamiques à l'écoulement dans la salle d'essai telles que vitesse de l'air, dépression. Les débits d'air requis par le moteur et par le refroidissement vont déterminer la section de salle d'essais et le choix d'un banc à une ou deux entrées d'air. Il faudra calculer les sections des entrées d'air et de l'échappement compte tenu des pertes de charges provoquées par la forme des canaux et des obstacles tels que panneaux et grillages.

Le problème de l'ingénieur acousticien est d'abaisser le bruit à un niveau imposé par l'utilisateur. Ce niveau dépend du lieu d'implantation du banc, de sa distance et son orientation par rapport aux habitations, ateliers, bureaux. Les niveaux maxima prescrits par les règlementations en matière de bruit sont le point de départ. Tenant compte des lois de transmission du son on peut calculer le niveau maximum à une distance de référence du banc d'essai. Il reste ensuite à l'ingénieur à déterminer l'isolation nécessaire, le type et la géométrie des panneaux acoustiques dans les entrées et l'échappement en respectant les exigences thermiques et aérodynamiques déjà formulées.

Les différents aspects seront complétés par des données numériques concernant les normes et les matériaux, ainsi que les résultats obtenus dans des bancs en usage.

Chapter 1. General description of the closed test-bed.

1.1. Introduction.

The more stringent requirements for protecting the environment against noise, on the one hand, and the high noise and annoyance produced by the turbojets, especially by military engines with afterburners, on the other hand, no longer allow the testing and trimming of engines in the open air or in a simple rainproof building. These tasks have to be performed in closed test-beds or using ground run-up suppressors with adequate noise insulation and absorption. Outside the test-cell the noise level must be acceptable for the people who work or live in the neighbourhood and has to meet the noise standards or regulations applicable in the country.

Some tests and performance checks are to be performed on the bare engine installed on a bench mounted in the test-room or engine-bay. Other maintenance work requires the trimming of the engine installed on the aircraft. There is a need for adequate buildings for these two types of tests.

The test-cell operating engineer and the procurement officer have to define the specifications with regard to :
- the noise inside test and control-room, the engine preparation area, the other rooms in the building, as well as outside the test-cell
- the airflow conditions, flow velocities and pressures in the test-room
- the required lifetime, especially for the acoustic panels and absorption material.

It is obvious that the test-facility's cost will depend on the requirements of the procuring agency, but also on the experience and competence of the design engineer rèsponsible for the plans and the choice of materials.

In this lecture we will stick to the study of the aerodynamic, thermodynamic and acoustic aspects and notions important to the test-cells design. This lecture's objective is to acquaint the engineer in charge of the testing with the basic knowledge necessary to work out the right specifications for a new test-building, and to evaluate the capability of an existing cell to test different or new type of engines. Other aspects relating to the building itself, such as the structure calculations of foundations and walls will not be covered.

1.2. General presentation (lay-out) of a test-bed.

The bare engine is fixed on a bench wich is installed in the test-room (fig. 1). The engine sucks in an airflow Qm through an intake stack provided with acoustic material in order to absorb the noise emitted by the engine and especially by the compressor. The engine's exhaust gases are ejected through an augmenter tube ejector mounted a short distance behind the engine exhaust. The gasflow Q1 is equal to the sum of the airflow Qm and the fuelflow. The high velocity gasflow has a pumping effect due to the ejector. A secondary airflow Q2 is sucked in through the eductor and mixes with the exhaust gases. The secondary air flows through the intake stack and the test-room and the temperature is very close to the ambient temperature outside the test-bench.

The velocity and temperature of the gases ejected by the engine depend on the type of engine and the throttle-setting. The temperature is particularly high in the case of an afterburner engine. The test-bed's exhaust stack must also be equiped with acoustic panels. In order to achieve an acceptable mechanical durability of these panels the exhaust gases' temperature must remain below a certain value. The secondary airflow Q2 mixes with the primary airflow Q1, so that the average temperature of the mixed exhaust gases is lowered to the required level.

The test-bed shown in fig.1 has vertical inlet and outlet stacks. The advantages of this arrangement are : the noise radiation at ground level is lowered due to the directivity effects, clean air is sucked in with less danger of foreign object damage and erosion of the acoustic walls. The construction of a horizontal inlet channel and/or outlet stack is less expensive but it may be necessary to augment the volume of noise absorption materials in order to meet the required noise attenuation. The airflow through a horizontal inlet channel without bends is less disturbed than it is in the case of the vertical stack which requires turning vanes to lower the distortion.

The test-cell is a set of buildings consisting of the test-bay with inlet and outlet channels, the control room, preparation area where the engine is fixed on an adapter, thus minimizing the non-running time of the engine in the test room, and the equipment rooms for the supply of the test-cell and engine with fuel, compressed air and electric power. The control room is often adjacent to the test-bay and the window may not be in the plane of the centrifugal forces of the turbines for obvious safety reasons. The engine can also be observed with closed circuit television, allowing the control compartment to be separated from the test room. Noise attenuation between test-bay and control-room can thus be improved when it is necessary to obtain a very low noise level in the control-room. This can be important when the test-cell is a training center for maintenance operators.

The access doors should never be located in the wall separating the test-section from the control-room, as the transmission loss value of a wall or a door is greatly increased by any leaks at the door's perimeter, along ducts or supply cables, as the leaks form a path for the transmission of sound power. The doors in the test-bay's walls

should be designed so that the depression in the cell closes the doors and compresses the gaskets and seals.

The trimming of the engine installed in an aircraft is the second problem. If the required attenuation is not too important, a simple run-up noise suppressor is used, consisting of an ejection channel provided with sound absorbing materials and linked to the engine exhaust (fig.2). It is obviously the least expensive noise suppression system. The noise emitted by the compressor and radiated forward through the air intake is not attenuated. In the case of combat aircraft equiped with turbofan engines with afterburners, the acoustic requirements can only be met if the complete aircraft is installed in a building with adequate air intake and exhaust stack (fig.3). The air intakes are at the front, in the sliding doors giving access to the test area or in the upper part of the side walls. The control room of this hush-house is not always necesssary, sometimes it is a simple room with few instrumentation.

1.3. Lay-out of the buildings.

The customer should carefully study the workload consisting of engine testing and trimming an aircraft, as well as the building's locations on the airfield because the grouping of test-stations will reduce the cost. If the number of engine tests is important and imposes the construction of two test-bays, they will be parallel with the single control-room and engine preparation area between the two tunnels. If the work organisation allows it, the engine test-station and the aircraft trimming bay (or hush-house) can be built side by side (fig.4). If there is no need for simultaneously testing of bare engines and trimming of aircraft, a single building with one test-bay provided with a movable enginestand is the most economical solution (fig.3).

Chapter 2. Thermo- and Aerodynamic considerations.

2.1. Test-cells with air cooling and water cooling.

The acoustic panels in the test-cell's exhaust stack consist of fibrous noise absorbing material held between two perforated metal sheets. The quality of steel and absorbing material and the required durability of the acoustical treatment determine the allowable temperature and velocity of the cell exhaust gases. The temperature limit is about 400°C.

The temperature of the exhaust gases of military jet engines in full-afterburning is as high as 1800°C and, in maximum dry regime, between 500 and 700°C. in a dry test-cell the engine exhaust gases must be cooled exclusively by mixing them with ambiant air requiring large secondary airflows which we will calculate later in this paper. By injecting water into the hot gasflow in the augmenter tube, the cooling effect is obtained with smaller secondary airflows.

2.2. Test-cell with air cooling. Dilution ratio.

Fig.5 shows the flow conditions in the inlet section 0 of the augmenter tube. The secondary airflow Qa is sucked in by the pumping effect due to the high velocity of the turbojet exhaust gases. We assume a steady one-dimensional or uniform gasflow in section 5. Actually the distance from section 0 to section 5 is too short to allow the complete mixing of hot and cold gases. To improve the mixing process, bars or rods can protrude radially into the exhaust flow from the ejector tube or a perforated cone or cylinder can be fixed to the augmentor outlet.

The equation of energy conservation between sections 0 and 5 becomes

$$Q1(h1+(v1)^2/2)+Qa(h2+(v2)^2/2) = (Q1+Qa)(h5+(v5)^2/2) \qquad (2.1)$$

h : static enthalpy in sections 1,2,5
Qa: secondary airflow
v : velocities in sections 1,2,5
$h+(v)^2/2 = ht$: total enthalpy

The calculations are simplified by the use of the mean specific heat Cp (J/kg.K) instead of the enthalpy. The total temperature Tt2 of the secondary air in section 0 will be taken equal to Tambiant=15°C or 288K. As the velocity v5 is also limited by the durability of the exhaust acoustic panels to about 40m/s, the kinetic energy $(v5)^2/2$ is small compared to Cp.T5. Formula (2.1) can be written as

$$Q1.Cp'(Tt1-T5) = Qa.Cp''(T5-288) \qquad (2.2)$$

The temperatures are in °K, Cp' and Cp" are the adequate mean specific heat for gas and air.

The temperature T5 has to be calculated, and introducing CJ=Cp'/Cp" we obtain

$$Tt5 = T5 = \frac{Q1.CJ.Tt1+Qa.288}{Q1.CJ+Qa} \qquad (2.3)$$

An accurate choice of the values of the mean specific heat Cp is a problem. In section 0 we have the input of exhaust gases at t° Tt1 at a high fuel flow over air ratio

of up to 6% in full afterburning, and pure air. Gases and air mix between sections 0 and 5 and the ratio fuel flow over (Qm+Qa) changes and drops to a low level of 1%. The available graphs (fig.6) or the polynomial expressions of Cp (ref.1) gives Cp=dh/dT for gases with constant fuel to air ratios.

We can admit :

$$Cp' = \frac{Cp(Tt1)+Cp(Tt5)}{2} \qquad (2.4)$$

Cp is the value of the specific heat for the total fuel to air ratio of the engine at temperatures Tt1 and Tt2.

$$Cp'' = \frac{Cp(Tt5)+Cp(15°C)}{2} \qquad (2.5)$$

Cp for air (air to fuel ratio = 0%) at the temperatures Tt5 and 15°C.

We calculated the relation between T5 and the dilution ratio Qa/Q1 for different temperature values Tt1 (fig.7). If the upper exhaust temperature limit is 400°C the required dilution ratio Qa/Q1 is greater than 5.3 in the case of full-afterburning. We will discuss later the consequences of this high ratio on the test-cell's design.

2.3. Test-cell with watercooling. Required waterflow.

To lower the needed secondary airflow, the cooling can be obtained by injection of water in the eductor tube. The vaporization of the water and the heating of steam absorb heat and cool the hot gasflow.

We can calculate the final temperature T5 as a function of the flows Q1 and Qa and the waterflow Qw. We again must assume that the flow in section 5 is homogeneous, thus the totality of injected water has been vaporized and heated to t° T5. This is not as evident as one might think because part of the water used in spray-cooling is lost through the stack (ref.2). The high temperature jet core is not thoroughly penetrated by the injected water.

The conservation of total energy :

$$Q1.Cp'.(Tt1-T5) = Qa.Cp''.(Tt5-288)+Cpw.Qw.(373-Tw)+Lw.Qw+Cpsteam.Qw.(T5-373) \qquad (2.6)$$

To the equation (2.2) we add the terms corresponding to :
- heating the water from inlet t° Tw (10°C) to the vaporization t° of 100°C (373K)
- vaporization of the water Lw.Qw; the value of the vaporization heat Lw is 2257 kJ/kg
- heating the steam from 100°C (373K) to T5; Cpsteam can be taken equal to 1.98 kJ/kg.K.

If we know the value of the dilution ratio Qa/Q1 we can calculate Qw as a function of T5 by transforming equation (2.6)

$$\frac{Qw}{Q1} = \frac{Cp'(Tt1-T5)-(Qa/Q1)Cp''(T5-288)}{4187(373-Tw)+1980(T5-373)+2.26\ 10^6} \qquad (2.7)$$

Fig.8 gives the required Qw/Q1 to lower the temperature of the mixed gases to T5 when Tt1 is equal to 1800°C and for different values of the dilution ratio R=Qa/Q1.

For example assume R=2 and a final t° T5=300°C, we need Qw/Q1=0.36. This leads in the case of a F100-PW100 engine with Q1=106kg/s to a waterflow of 2.5 m3/min. Actually the required amount of water will be higher due to the incomplete vaporization.

In the calculations of the flow areas in the exhaust stack we need the value of the mixed gas's specific volume $1/\rho$:

$$\frac{1}{\rho} = T5\left(2.83+4.54\ \frac{Qw}{Q1+Qa}\right)10^{-3} \qquad (2.8)$$

2.4. Air velocities in the test-room.

As the figures show, the secondary air flows through the rest-room to the eductor tube inlet. The air velocities ahead of the engine must be limited, as we explain later. These velocity limits are important because they determine the required airflow area or cross-sectional area of the test-room. The building's cost will be greatly influenced by these cell-bay dimensions.

The stall and pumping phenomena will appear if the distortion of the airflow upstream of the compressor or fan is too high. Several distortion indices are defined in the stall theory but cannot be used in our problems.

No method is available for predicting the distortion index downstream of the inlet duct. We mention the simple rule given by General Electric (ref.2). Total distortion greater than 50mmH2O above or below the average is unacceptable and it is recommended to keep this difference to less than 25mmH2O.

The distortion depends on the duct shape of the air inlet stack, the flow dividing

obstacles and their profiles (acoustic panels), the shape and number of bends, the number and profile of the turning vanes, the wire mesh and bird duct screens, the flowlength between the downstream edge of the panels or airflowstraighteners and the engine inlet where vortexes and wakes are damped.

In any case the flow perturbations are unavoidable and the resultant distortion will augment with the air velocity. Therefore the rule is to set an upper limit of 15m/s in the test-room section upstream of the engine.

The obstacles in the test-rooms as staircases, overhead or side beams, benches and adapters to thrust stands, service stands, access doors can also produce unacceptable flow distortion. If necessary some testing of the airflow must be performed on scale models of the test-cell (ref.3). "The need for smooth laminar flow at the compressor inlet cannot be overemphasized" (ref.4).

The velocity upstream of the bellmouth must also be limited. The engine thrust depends on this air velocity because the equilibrium running point of a turbojet engine is a function of the flight Mach number. If the air velocity is too high, a thrust correction must be applied for ram pressure.

The direct method for measuring the thrust uses a dynamometric device mounted between the bench and the stand on the floor or suspended from the ceiling. The force is not a correct measure of the thrust when the air velocity along the engine and the bench is too high. This airflow exerts aerodynamic forces on the engine envelope and accessories, the bench structure, forces which are substracted from the thrust. The value of the correction can be determined from calibration measurements in the test-cell but cannot be calculated. The velocity of the airflow as it passes the cross-sections between the engine and the ceiling, walls and floor must be kept under 6m/s.

2.5. Velocities and depression in the vicinity of the engine exhaust.

The outlet section of the jet exhaust duct must be correctly positioned in relation to the entrance to the eductor tube. In the convergent intake of the ejector tube the secondary air's velocity is augmented and the pressure lowered (fig.9). If the turbojet outlet section penetrates too far into the convergent intake, the thrust will not be measured correctly for the following reasons.

The outer envelope of the exhaust duct and nozzle is in a zone of low pressure and high freestream velocities. Friction and pressure forces exerted in opposite direction of the thrust appear on the outer envelope of the exhaust duct. The pressure on the engine outlet section is lower than that in the test-room. This alters the thrust developed by the engine due to the influence on the equilibrium running point for a non-saturated nozzle and the appearance of a pressure term A9(p9-pamb) in the expression of thrust in the saturated exhaust.

The outlet section of the engine nozzle must be upstream of the inlet section of the eductor tube; the recommended distance is one enginenozzle diameter. The volumeflow of the secondary air is lowered when the distance is reduced so the dilution ratio R can be changed through the positioning of the engine in relation to the augmenter tube. The jet noise radiates through the augmenter inlet and if the distance between engine nozzle and ejector increases the noise level in the test-room rises.

Due to the secondary airflow through the test-tunnel there can be unacceptable negative pressure gradient along the engine outer surfaces from in- to outlet. In the case of frontfan-engines a difference of the back pressures on the fanflownozzle and the coreflownozzle changes the thrust developed by the engine. In an open air test there is no pressure gradient and back pressures are equal to upstream pressures.

2.6. Internal and external recirculation. Temperature distribution.

The airflow in the test-bay and the gasflow in the augmenter must remain unidirectional and without recirculation. Due to excess back pressure in the augmenter or exhaust stack the hot gases could return forward along augmenter and cell walls to the engine inlet. The temperature at the compressor inlet could thus rise and there could be a significant temperature distortion. The average temperature at the inlet influences the thrust and it has to be corrected to standard conditions.

This correction is quite important and an error in the average temperature leads to unacceptable errors on the thrust. Air or gas recirculation causes uneven temperature distribution and it is difficult or even impossible to determine the average temperature at bellmouth inlet with a small number of thermocouples.

With a high secondary airflow or dilution ratio there is little likelihood of air recirculation in the test-bay. The excess back pressure may appear when the pressure losses due to water injection rings, rods or bars, diffusor or colander, bends, acoustic panels are too high. The pressure losses are proportional to the loss coefficient and the kinetic energy of the gasflow. In the case of hot gas recirculation the back pressure can be alleviated by reshaping the obstructions, increasing the flow area through the diffusor and exhaust stack, installing a recovery diffusor or an expanding bellmouth at the exhaust stack's outlet, reducing the secondary airflow if allowable in relation to the exhaust temperature limits. The dilution ratio can be reduced by lowering the diameter and/or the length/diameter ratio of the augmenter, or reducing the distance

between engine outlet and eductor inlet.

The external cell recirculation consists of the reingestion of the hot gases ejected through the exhaust stack. By proper cell design, taking into account the prevailing wind direction, and vertical separation of the upper sections of exhaust and intaks stacks, the external recirculation can be minimized. Strong winds in the exhaust-intake direction can nevertheless cause recirculation. A horizontal inflow reduces the likelihood of hot gases ingestion.

2.7. Cell depression.

The ambiant pressure for the engine is the static pressure in the test-bay. The thrust value must be reduced to standard pressure of 1.013 bar. The pressure in the test-bay is lower than the outside pressure. The depression is due to the dynamic pressure loss resulting from the velocity (vt) in the test-bay and from the flow pressure losses in the air intake duct (flow open area, bends, acoustic panels, screens).

It is generally recommended to limit the depression to a maximum of 150 mmH2O. The reason is not the structural load limit but the correction on the measured parameters and the operation of the engine in conditions similar to those existing in open air test-stand. In the test-cells of National Research Council, Canada, the test-engineers try to keep it below 25 mmH2O (ref.5).

2.8. Engine oscillations due to pumping of secondary air.

The very small cyclic variations in fuel and airflow which are not noticeable in an outdoor stand can be amplified in the closed cell environment (ref.4). This is due to the interaction of the exhaust jet through the pumping effect on the pressure at the engine inlet. In some cases it can be difficult to obtain stable measurements. The causes are a small cross-sectional area of the test-room and/or a short distance between engine and augmenter tube inlets.

2.9. Cross-sectional area of the test-room. Test-cell with two air-intakes.

The required engine and secondary airflow and the velocity limitations in the test-room enable us to calculate the cross-sectional area A using the flow formula $Q = A.v.\rho$.

This formula has to be applied twice :

- in the section upstream of the engine inlet $(Qm+Qa) = At.vt.\rho$ (2.9)
  - where At : total cross-sectional area of test-bay
  - vt : maximum 15m/s upstream of engine
  - ρ : ρ ambiant (=1.25 kg/m3)
- in the section downstream of the bellmouth $Qa = Ae.ve.\rho$ (2.10)
  - where Ae : cross-sectional flow area of the test-tunnel downstream of engine inlet (area At minus engine and bench cross-sectional areas)
  - ve : maximum 6m/s
  - ρ : ρ ambiant (=1.25 kg/m3)

One of these results will be the most stringent and will determine the test-bay's cross-dimensions. Of course the cross-section must be large enough to allow the mechanics to work on the engine and to provide sufficient space between bellmouth and walls, ceiling, floor to avoid flow distortion. In high bypass ratio engines the dilution ratio R can be small on a thermodynamic basis and thus leads to a small cross area of the test-room in comparison to the bellmouth.

Let us calculate the sample of an afterburner engine of 12,000 daN thrust. The exhaust gasflow Q1 is 110 kg/s and total temperature is around 1750°C. To obtain the average exhaust gas temperature equal to 300°C we need a dilution ratio close to 6. The total airflow (Qm+Qa) upstream of the engine inlet is (110+660)kg/s and the area At=41m2. The flow area between engine and rest-room walls, taking ve=5m/s must be 105m2. The total cross-sectional area is near 110m2 or 10.5m by 10.5m.

Such test-bay and augmenter tube dimensions give rise to a high cost for the test-tunnel. There is a need for other solutions.
The first one uses water-cooling with a reduction of the secondary airflow to obtain a normal dilution ratio of 2 to 2.5. We mentioned that the waterflow is quite high and watercooling has several drawbacks. "Water spray has a deleterious effect on air quality and acoustic absorptive treatments" (ref.6). "Watercooling may in itself be a source of pollution" (ref.2). The waterdroplets can absorb sulfur dioxyde and cause corrosion in- and outside the test-station. The exhaust stream's humidity can condensate on the roads nearby and cause icing up at low temperatures. Sometimes water is too scarce to be used for cooling. A dry cooled facility would have long term cost advantages over one with water-cooled exhaust system (ref.7).
The second solution consists of a test-bed design with two air-intakes or inlet-stacks. An example is shown on fig.10 realised at F.N. and at the Belgian Air Force bases. The engine airflow Qm and a part of cooling air Q2 (2 to 3 times Q1) is sucked in by the first air-intake and flows through the augmenter tube. The second part of cooling air Q3 is pumped by the augmenter tube's exhaust jet into the test-bed's outlet channel and mixes with (Q1+Q2). The two ejectors are in series. The test-room's cross-sectional area is determined by the airflow (Qm+Q2).

The second air-intake can also emerge at the test-room's downstream end in front of

the augmenter tube (fig.11). In this case the airflow in the test-room can be disturbed and the eductor tube must be very large to take the total flow (Q1+Q2+Q3).

2.10. Cell airflow calculations of the test-bed with one ejector.

2.10.a. Augmenter tube.

We consider the configuration shown in fig.1 and 11. The flow in the exhaust stack and between the acoustic panels must be as uniform as possible. With a simple cylindrical eductor tube which exhausts in the channel upstream of a vaneless bend, exhaust gases tend to accumulate near the back wall and cause high velocity flows in the area near this wall. The high velocities in this non uniform flow reduce the acoustic treatment's life and generate noise at the outlet. Turning vanes (fig.11) or a colander (fig.1) are used to improve flow uniformity in the exhaust stack. The colander, a cylindrical or conical diffusor with holes, is fitted at the augmenter tube's extremity. The total open area through the diffusor holes must be 40 to 60% in excess of the eductor tube's cross-sectional area (ref.4). The holes should not be too small in order to avoid clogging by carbon deposits. The exhaust's low frequency noise is changes into a high frequency noise which can be attenuated more easily by the acoustic material.

We establish the theory for the test-bed with one air-intake fig.1. It is easily extended to the case of fig.11.

In the eductor tube hot gases and cold secondary air mix in the annular mixing region (fig.12). To obtain a uniform flow the tube would have to be quite long. Actually, to keep the cost down, the tube will be shorter. In the theory we assume that the flow is uniform in outlet section 4 (velocity v4, pressure p4, t° T4). The theoretical value of the pumped secondary airflow Q2 must, if necessary, be multiplied by a airflow pumping efficiency to obtain more realistic values. The flow in section 2 of fig.13 consists of a unidimensional core flow Q1 through area A1=A9, surrounded by a uniform flow Q2 through annular area A2. The momentum equation applied to the fluid between sections 2 and 4 :

$$p2.A2+p1.A1-p4.A4-FW=(Q1+Q2).v4-Q1.v1-Q2.v2 \qquad (2.11)$$

(A1+A2) is the total area of the eductor tube's cylindrical part and equal to A4. We ignore the influence of a divergent part of the tube.

The engine nozzle outlet (area A9) is some distance upstream of section 2 and we assume a cylindrical jet between sections 9 and 2.

The friction force FW is exerted by the tube's inner surface on the gases between sections 2 and 4. The velocity near the inner surface is v2 for a long distance and we admit the classic formula for pressure losses in pipes :

$$FW=(KAT)\,\frac{Ld}{Dd}\,\frac{\rho 2.(v2)^2}{2}\,(A1+A2) = (KAT)\frac{Ld}{Dd}\,(Q2)^2\,(A1+A2)/2.4(A2)^2 \qquad (2.12)$$

if we introduce $v2=Q2/\rho 2.A2$ and $\rho 2=\rho amb=1.2$ kg/m3
KAT : loss coefficient in the augmenter tube, function of the Reynolds number.

Introducing the expression of the engine thrust

$$F = Q1.v1+(p1-p2).A1 \qquad (2.13)$$

and the velocity $v4=(Q1+Q2)/A4.\rho 4$ we obtain

$$F+p2(A1+A2)-p4.A4-FW = \frac{(Q1+Q2)^2}{\rho 4.A4} - \frac{(Q2)^2}{\rho 2.A2} \qquad (2.14)$$

The specific mass $\rho 4$ is equal to p4/R.T4. In section 4 pressure p4 exceeds atmospheric pressure by about 200 mmH2O in order to expell the gases through the downstream bend and exhaust channel. This small overpressure has virtually no influence on the value of $\rho 4$, so

$$\rho 4 = 10,3.10^4\,/287.T4 = 360/T4 \qquad (2.15)$$

The momentum equation is written

$$F+(p2-p4)(A1+A2)-FW = \frac{(Q1+Q2)^2.T4}{360.(A1+A2)} - \frac{(Q2)^2}{1,2.A2} \qquad (2.16)$$

We consider the energetic equations established in section 2.2, formula 2.2 and 2.3 for the dry cell, and applied between sections 2 and 4.

Equation (2.3) gives Tt4. The Mach number in section 4 can be about .4 and Tt4 is equal to about 1.03 T4. We obtain

$$Tt4 = \frac{CJ.Q1.Tt1+290.Q2}{CJ.Q1+Q2} \approx 1.03\ T4 \qquad (2.17)$$

Equations (2.16) (with FW given by (2.12)) and (2.17) enable us to calculate the two unknowns Q2 and Tt4 as a function of the pressure rise (p4-p2) for a given engine

performance and augmenter geometry. An example is shown on fig.13. As the pressure difference (p4-p2) increases, the airflow Q2 decreases.

As we pointed out already the theoretical value of Q2 can be corrected by multiplying this Q2 with a pumping efficiency which depends on the augmenter geometry (length/diameter and ratio (A2+A1)/A1) and position of engine nozzle related to augmenter inlet.

The augmenter tube's diameter is usually 3 times that of the engine nozzle exit diameter and A1/A2 is about 1/8. To obtain an acceptable airflow pumping efficiency the length/diameter ratio should be greater than 8. Usually the ratio is between 6-8 to 1.

2.10.b. Pressure losses in the intake and test-room.

The velocities of the air in the intake channel and the test-room are small and we apply the Bernoulli equation between a free air section outside the intake and section 2. The secondary air's velocity v2 can be high but we ignore the compressibility effects.

$$pa-p2 = (KEC)\ \frac{\rho a.(vt)^2}{2} + (KEA)\ \frac{\rho 2.(v2)^2}{2} + \frac{\rho 2.(v2)^2}{2} \qquad (2.18)$$

KEC : intake stack's loss coefficient (geometry of the channels, number of bends, turning vanes, grids, acoustic panels and flow areas)
KEA : loss coefficient related to the secondary airflow washing the engine's outer surfaces, equipment and bench, and entering the augmenter's tube convergent cone.

Using the massflow equations $Q = A.\rho.v$ and $\rho a = \rho 2 = 1.2$ kg/m3 we obtain

$$pa-p2 = KEC\ \frac{(Qm+Q2)^2}{2,4.(At)^2} + (KEA+1)\ \frac{(Q2)^2}{2,4.(A2)^2} \qquad (2.19)$$

We use At as reference area for the pressure losses in the intake channel.

2.10.c. Pressure losses between section 4 and exhaust outlet.

The outlet section 6 (fig.11) of the exhaust channel is at atmospheric pressure. (If a divergent expanding bellmouth is installed at the exhaust's outlet, the pressure in section 6 can be below atmospheric pressure).

Bernoulli equation applied to the gases between sections 4 and 6 :

$$p4+\frac{\rho 4.v4^2}{2} = pa+\frac{\rho 6.v6^2}{2} + (KST).\frac{\rho 6.v6^2}{2} + PL(4-5) \qquad (2.20)$$

Kinetic energy $(v4)^2/2$ can be partly recovered if the augmenter tube is provided with an adequate expanding conical duct from area A4 to A6. To avoid flow detachement the cone angle would have to be small and the length of the duct would be prohibitive with subsequent high friction losses (and cost). We admit the approximation that the dynamic pressure $\rho 4.(v4)^2/2$ is not recovered and compensates for the friction pressure loss PL(4-5) between section 4 and section 5 at the vertical exhaust stack's inlet.

The loss coefficient (KST) is related to the flow between sections 5 and 6 provided with acoustic treatment.

To simplify the expression (2.20) we assume :
- adiabatic flow without air supply between sections 4 and 6, so Tt4=Tt6 and equal to T6 because v6 is small as already mentioned in section 2.2. Velocities v5 and v6 are roughly 40m/s.
- the specific mass $\rho 6$ is given by pa/r.T6 and can be approximated to

$$\rho 6 = \frac{pa}{r.Tt4} = \frac{1.013\ .10^3}{1.03\ .r.T4} = \frac{340}{T4} \qquad (2.21)$$

The pressure difference p4-p6=p4-pa is calculated from (2.20), introducing mass flow equati

$$p4-pa = (Q1+Q2)^2\ .T4.(1+KST)/680.(A6)^2 \qquad (2.22)$$

Summing up equation (2.19) and (2.22) we obtain the pressure rise in the augmenter tube :

$$p4-p2 = (KEC.(Qm+Q2)^2/2.4\ (At)^2) + ((1+KEA).(Q2)^2/2.4\ (A2)^2) + ((1+KST).(Q1+Q2)^2\ .T4/680.(A6)\ )^2 \qquad (2.23)$$

The equation (2.17) gives the relation between T4 and Q2. The two equations (2.17) and (2.23) enable us to calculate the pressure rise in the augmenter tube (p4-p2) as a function of Q2 for given values of loss coefficients, test-cell areas and engine performances. The solution is given by the intersections of the curves in fig.13.

2.11. Example of calculations for an engine in max dry and max afterburning regime.

The equations have been solved for the following numerical values and plotted on fig.13.
- performances of a modern military turbofan engine in maximum dry regime : F=65000N; Tt1=755K (482°C); A9=A1=0.66m2; Q1=105kg/s
- some test-cell and augmenter dimensions of the F.N. test-building at Liège, which in reality has two air-intakes as shown in fig.10 and is designed for testing afterburning engines with higher thrust and airflow than the F100-PW100. We imagine this test-bed with a closed secondary air intake (Q3=0) and a lengthened eductor tube to 20m. The dimensions used in the calculations are At=49m2; A6=59m2; Dd=2.5m; Ld=20m; A2=4.25m2 and the estimated loss coefficients KEC=4.250 and KEA=0.2.

The real airflow Q2 will be lower than the results indicated in fig.13.

This test-cell is over-sized for the testing of this engine in dry regime. The exhaust stack's area is very large for the airflow. A rough calculation of the velocity v6 gives (Q1+Q2)/A6. ρ6 = 450/59.3x0.9 = 8.5m/s which is small compared to the allowed 30 to 40m/s. This explains why the influence of the loss coefficient KST is so small on the airflow.

We shall make the calculations for the same engine in maximum afterburning regime : F=108000N; Tt1=1750°C; A1=0.66m2; Q1=110kg/s; and the same test-cell.

The curves (p4-p2) on f(Q2) are drawn in fig.14. Comparison with fig.13 shows that the curve's slope (equation (2.16)) is changed, the secondary airflow decreases slightly but the t° T4 and T6 exceed the allowable limits related to the acoustic treatment.

Watercooling would be necessary in this cell configuration. The formulas remain the same, momentum, energetic, pressure losses equations, but one ought to take into account the specific masses ρ4 and ρ6 given by formula (2.8) and the mass flow (Q1+Q2+Qw) in the eductor outlet and exhaust stack. The calculations are approximate as it is difficult to predict the amount of water that will not evaporate. Thermocouples will measure the temperature in the exhaust stack and adjust the waterflow to obtain a temperature below the acceptable value.

2.12. Test-room depression. Loss coefficients. Intake and exhaust areas.

The test-bay depression is calculated by the Bernoulli equation applied to the airstream between a free air section outside the intake and the section upstream of the engine bellmouth.

$$(\Delta p)\text{cell} = (\text{KEC})\ \frac{\rho a.(vt)^2}{2} + \frac{\rho a.(vt)^2}{2} \qquad (2.24)$$

with vt = (Qm+Q2)/At. ρa.

The velocity vt is limited to 15 m/s and the maximum value of the dynamic pressure (ρa)(vt)^2/2 is 140 Pa (14mmH2O). The pressure loss in the intake, proportional to the loss coefficient KEC, must be limited taking into account the acceptable or maximum allowable depression level.

This indicates the importance of the loss coefficient which must be predicted with the classical theory of the airflow in ducts with different obstructions and the experimental coefficients found in engineers' mementos (ref.8).

The expression for a pressure loss due to one obstruction is of the form k. ρ.v^2 /2 where v is the local velocity in the open flow area v=Q/A.ρ and k a coefficient function of Reynolds number, aerodynamical shape, length, rugosity of the obstructions, angle of the bend and number of turning vanes.

The expression shows the importance of the open flow area A which is the physical parameter that the design engineer can augment to lower the pressure loss if necessary.

In the intake channels the acoustic panels block about 50% of the total area. The first calculation of the intake's area shall be based on the velocity limit of the flow between the acoustic panels. Going back to our example in section 2.11, the intake airflow is about 350+103 = 450kg/s. If the maximum velocity is 30m/s, the required open area is 450/1.25x30 = 12m2. The total intake area must be 24m2.

If we consider a test-cell with an air-intake area equal to the test-bay area of 24m2 and an estimated loss coefficient of 5, the cell depression would be

$$(\Delta p)\text{cell} = (\text{KEC}+1)\ \frac{\rho a.(vt)^2}{2} = 845 \text{ Pa} = 86\text{mmH2O}$$

If this depression is above the value specified by the customer, the open area must be increased. As we already mentioned, the F.N. test-cell has been designed to test larger engines than the F100 and has an intake area of 49m2, equal to the test-room cross-sectional area. Limiting the velocity vt to 15m/s the maximum airflow allowed in this test-bay would be ρa.vt.At = 919kg/s and the resulting cell depression about 85mmH2O.

An accurate value of the loss coefficient KEC for the total inlet channel cannot be predicted. The values in textbooks and mementos are approximate and given for isolated obstructions (grids, panels, bends) with a smooth airflow upstream of the row. In the intake the obstructions are installed in successive rows and produce non uniform flow patterns which cannot smooth out in the short distance between two successive rows.

There is no difficulty in calculating the required exhaust area based on the massflow equation and the maximum value of the gas velocity between the acoustic panels. These also block an area that can be assumed to be 50% of the total exhaust area. The theory shows that pressure losses will influence the secondary airflow and dilution ratio. If losses are too important, an unacceptable back pressure may build up , causing recirculation of the gases. Increasing the open area will decrease the pressure loss. The mass flow equations are written for a uniform gasflow and one ought to make sure that this assumption is reasonably well fulfilled. In the case of a non uniform velocity field the loss coefficient KST cannot be properly predicted and will increase.

2.13. Cell airflow in a double air-intake test-bed with two ejectors in series.

The theory of the test-bed with two ejectors in series as shown in fig.10 rests on the same principles of momentum, energy and pressure loss as the simple test-cell already studied. Momentum and energy equations must be applied twice, first on the augmenter between sections 2 and 7, secondly on the ejector between sections 7-8 and 4.

It is not the lecture's purpose to describe the complete and detailed theory. This can be found in ref.9. We will only highlight the particularities of the physical phenomena in this double ejector flowfield.

The momentum equation (2.16) remains valid for the augmenter tube but the static pressure p7 in the outlet section is now lower than the atmospheric pressure. The airflow Q3 flows through annular area A8 with velocity v8 and this causes a depression (pa-p8). The augmenter outlet is not choked, Mach number M7 can be about .5 and the nozzle flow theory shows us that p7=p8.

In the momentum equation applied to the second ejector there appears the force exerted by the walls on the fluid between sections 7-8 and 4. There is of course the friction force given by formula (2.12) but with the introduction of the square or rectangular section's hydraulic diameter. The walls sometimes form a divergent duct and a second force due to pressure is given by int(p.dA) between sections A4 and (A7+A8). This integral can be approximated by

$$\frac{p8+p4}{2}.(A4-(A7+A8)) \qquad (2.25)$$

In this test-cell the augmenter tube is short in comparison to the length recommended in previous sections (8 to 10 times the diameter) and necessary to obtain a reasonably uniform outletflow. In the F.N. test-bed the length/diameter ratio varies between 2.5 and 3.5. This is important in the determination of the airflow Q2 which should be calculated as an integral of the massflow/area over the area A7.

The Bernoulli equation for the determination of the pressure losses must be applied to the first air-intake, the second one and the exhaust channel. Besides the loss coefficients and areas KET, At (first air-intake) and KST, A6 (exhaust stack), we introduce KES and A3 for the second air-intake.

Altogether we obtain more equations than previously and these contain more physical parameters which influence the results. We arrange the equations and three independent groups of parameters related to the pressure losses in the three channels appear :

$$(KET)/(At)^2 \quad ; \ (KES)/(A3)^2 \quad ; \ (KST)/(A6)^2$$

The equations' numerical solutions for different combinations of the independent parameters are calculated and an example is given in fig.15 calculated for engine F100 in full afterburning installed in the F.N. test-bed. The graph shows that the influence of the loss coefficient/(area) is small on the airflow Q2 but strong on airflow Q3 and final temperature T4. The airflow Q2 in the augmenter tube depends on the pressure difference (p7-p2) which is slightly dependent on the losses in the intake and exhaust stacks.

The theory assumes a uniform flow in the eductor outlet sections, second ejector inlet and outlet. In reality, especially at the short eductor tube's outlet, the mixing is not complete, momentum and airflow are lower than the theretical values. In the F.N. test-cell some measurements were made. The average velocity behind the acoustic panels in the first intake channel was 8.30m/s in full afterburning. The temperature on the exhaust's turning vanes was about 315°C or 588K. The massflow equation and the energy conservation (fig.7) enable us to calculate the approximate experimental values : Q2=390kg/s and Q3=240kg/s. Estimating the values of the loss parameters :

$$(KET)/(At)^2 = 1.77\ 10^{-3} \ ; \ (KES)/(A3)^2 = 4.88\ 10^{-3} \ ; \ (KST)/(A6)^2 = 2\ 10^{-3}$$

fig.15 indicates the theoretical values Q2=440kg/s and Q3=540kg/s. In the theory of the second ejector, one should take the non-uniform flow at the inlet into consideration to

improve the calculated values.

Chapter 3. Acoustic considerations on the design.

3.1. Introduction.

As we already mentioned, the test engineer and procuring agency have to specify the maximum noise level outside the test-cell, inside the control-room, in other rooms of the building, in the test-bay where some parts of the engine might deteriorate due to acoustic fatigue.

The design engineer has to calculate the noise insulation, taking into account the maximum allowable noise levels and the engine's noise characteristics.

3.2. Noise characteristics of jet engines.

The acoustic power level (PWL) of the jet engine depends on the type of engine (straight jet, low or high bypass-ratio turbofan, afterburning engines) and on the operating conditions. This is due to the fact that the radiated acoustic power increases strongly with the exhaust gas velocity. The acoustic power W radiated from a jet is approximately proportional to the exhaust area A9 and jet velocity v9 to the eightpower.

$$W \div \rho a.A9.(v9)^8 \qquad (3.1)$$

The gasflow $Q1 = \rho a.v9.A9$ and the static thrust $T = Q1.v9$. The acoustic power is thus proportional to $T.(v9)^6$. Going from straight jet to high bypass-ratio turbofans, the exhaust velocity diminishes but the compressor and the large fans become important noise sources. In military turbofans operating in full afterburner, the jet velocity is very high and reaches about 1000m/s. A turbojet's thrust decreases when ambient temperature increases and the radiated sound power will be less on a hot than on a cold day. This is important in the evaluation of a test-bed's noise insulation performance.

It is not practical to express the power of noise sources in Watts and the "Acoustic Power Level" is introduced :

$$PWL = 10.\log_{10} W/Wo \qquad (3.2)$$

The reference sound power Wo is 10^{-12} Watt and PWL is given in dB(re 10^{-12} W). An afterburning engine's overall power level is about 160dB (10^4 Watts), compare this with the voice-conversational level of 70dB (10^{-4} Watts). The PWL for the F100 engine are given in fig.16 for two angles.

The acoustic energy is radiated in the volume surrounding the noise source and leads to a sound intensity I in W/m2 at a distance r from the source. I is related to the effective pressure. The Sound Pressure Level SPL is given in dB :

$$SPL = 10.\log(I/Iref) = 10.\log(p^2/pref^2) \qquad (3.3)$$

with $Iref = 10^{-12}$ W/m2 or $pref = 2.10^{-5}$ Pa.

The SPL at a point in space at a given distance from the source is not exclusively determined by the source's PWL and the distance but also by the surroundings. The source can be in free air (flying aircraft) or located near the ground in a semihemispherical open area (engine in an open air test-bed) or in an enclosed area as in the test-bay where the sound waves are partially reflected by the walls and propagate through the intake and exhaust.

The PWL and SPL are also characterized by the frequency spectrum. The octave, 1/3 octave or small band analysis are used and are important in this study for the following reasons :

- The human ear is not equally sensitive to all sound frequencies in the hearing range between 20Hz and 16kHz. The objective SPL in dBlin is not a good measure of a noise's level. Using an attenuation filter (A) as weighting network in the sound level meter, a more appropriate subjective noise level in dBA is obtained. We also need the noise criteria indoors which are given by the noise rating (NR) curves. These specify the dB levels in each octave band as given in fig.17.
- The engine noise spectrum depends on the jet velocities, exhaust geometry and the compressor, the latter tends to produce high SPL at certain frequencies (fig.18) (ref.10). The acoustic engineer needs to know the engine power and sound spectrum in order to choose the most efficient sound absorbing material and test-cell intake and exhaust devices.
- The sound waves are radiated in the surroundings and sound energy is extracted by the air molecules. To the attenuation due to the increasing distance (the sound energy is radiated through a spherical surface centred on the noise source and the surface increases with the square of the distance), one must add the attenuation due to "molecular absorption". It is a function of the air temperature and humidity, and of the sound frequency. Fig.19 gives the total SPL reduction with distance relative to the levels at 250 feet from the test-cell centre for the octave bands (ref.11).

The directivity of noise sources, as the jet engine and the test-bed's intake and exhaust channels is also important for the design. In afterburning conditions the highest

noise levels are aft of the engine at 120° from the forward pointing engine axis. The compressor noise is mainly radiated forward and in high bypass ratio turbofans the sound power generated by the fan is important.

Fig.20 shows the SPL in dBlin of the F100 engine in full afterburning conditions, installed in an open air test-bed. The noise levels of over 140 dB near the engine can cause permanent deafness over a very short time. Even with good helmet protection the maximum exposure time near the engine is limited to five minutes per day (ref.12).

From the F16 Technical Order we reproduce fig.21-22-23-24 on the noise levels in dBA for an F16 airplane in afterburner, maximum dry and idle and the noise exposure limits. An example of an octave band spectrum is given in fig.25 (ref.13) for an engine with a 12000 daN thrust, installed on the aircraft. The figure gives the spectrum without and with a simple ground run-up noise suppressor.

All this information on the engine or aircraft's noise characteristics is needed by the acoustic design engineer.

3.3. Allowable noise level outside the test-cell.

The test-bed customer or procuring officer must specify the max allowable noise level at a reference distance of the test-bed centre, mostly taken as 250ft or 200m. Engine noise level minus allowable level gives the test-cell attenuation or insertion loss that must be obtained. The determination or choice of the maximum allowable level is very important, because the building's construction cost will increase sharply with decreasing allowable noise levels.

In the technical reports on noise control for test-cells (ref.11) the distance of 250ft is recommended. "At this distance, the measurement positions are far enough from the facility so that the measured insertion loss is valid for greater distances, but close enough so that atmospheric conditions will not unduly influence the acoustic measurements.

Once the test-cell's site is determined, the distances from the site to the different inhabited locations such as residential and recreational areas, workshops, schools etc must be measured. The list of all such places, their distances to the test-cell and the recommended or allowable noise levels must be compiled. In the case of houses or buildings the outdoor maximum level must be calculated by adding to the indoor criteria the proper noise reduction due to the walls and windows.

Recommended noise level values are mostly given in dBA or in Noise Rating numbers and a guide of indoor criteria is given in table 1 (ref.14-15). In P&W's facility planning manual we found the values given in table 2.(page 2.23)

Starting from the outdoor noise criteria NR for each location, the maximum noise level in each octave band at 250ft can be calculated using the reduction of SPL with distance given in fig.19.

This is only correct in the case of flat unobstructed areas. Large buildings or hills between noise source and receiver make up acoustical shields but also reflecting surfaces which can increase the noise energy radiated to another location. Wooded areas of leafy trees provide additional noise reduction but in the winter the reduction is negligible. The surroundings' acoustic properties must be carefully examined.

Often the work will be simplified and the procuring officer will only specify the maximum allowable loudness level LA in dBA at a given distance from the test-cell centre. This overall level must also be determined taking into account the test-cell's situation relative to residential areas, workshops, offices. The Belgian Air Force specified for their engine test-cells a maximum level of 70 dBA at 200m.

The octave band sound power levels at 250ft for a given combination engine-test facility may be available from past experience (fig.26). In that case the customer can perform the calculation from source to receiver. The octave band SPL at any distance can be calculated, and thus also the Noise Rating number and the loudness level LA. This can be useful to answer the question : "Is the test-facility presented by the manufacturer acceptable for the inhabited locations surrounding the planned site ?".

3.4. Acoustic test-cell design problems.

The sound energy generated inside the test-cell is transmitted through the test-section walls, the intake and exhaust channels to the receiver outside the test-cell.

The sound intensity in a given place is the sum of the sound intensities due to the three (walls and two channels) or four (walls and three channels) noise sources of the test-bed. How much wall insulation and channel absorption is required to provide the required attenuation ? The most economical solution is obtained by a more or less acoustically balanced test-cell. A balanced design means that all noise paths deliver the same amount of noise to the receiver (ref.16). This can obviously not be obtained in all frequency bands : the source is one only, but the walls and acoustic panels have different attenuation spectra.

In fig.27 we repeat the rule for the addition of SPL due to two or more sound sources, e.g. the contribution from the intake is 90 dB and from the exhaust 98 dB : the resulting SPL is 98.7 dB. If the first of the noise paths has a low noise contribution e.g. 10 to 20 dB less than the other, there is an excessive amount of acoustical treatment in the first path. We can decrease this attenuation by 10 to 12 dB without influencing the resulting level and can spare acoustical treatment.

The sound pressure level contributions of the test-cell's three or four paths or sources in a balanced design become :

SPL(each source) = SPL(MAX. ALL. REC.) - 10.log(3 or 4) (3.4)

where SPL(MAX. ALL. REC.) is the specified maximum allowable level for the receiver.

The design engineer must take this as a general guideline because the cost of insulation through thicker walls can be vastly different from the cost for supplementary absorption material in the channels. To determine the necessary wall insulation and noise absorption in intake and exhaust stacks the engineer has to know the SPL in the test-bay, and at the test-tunnel sections of intake and exhaust, the so-called noise input sections of acoustical treatment.

Most of the noise is radiated into the eductor tube towards the exhaust acoustical treatment (ref.17). The sound power is equal to the product of intensity I times area A. This becomes :

SPL(exhaust input) = PWL - 10.log A(exhaust) (3.5)

PWL is the open field power level of the engine exhaust.

To determine the SPL in the test-section's reverberant field we can apply the classical theory rules for sound in large rooms.
The SPL will be a function of :
- the sound power radiated into the test-room by the engine; power is generated by the engine inlet (fig.20-23) and a small amount of the exhaust sound power is reflected by the detuner cone in the room. We have already mentioned the influence of the relative position of the engine exhaust to the augmenter inlet on airflow and noise.
- the room characteristics, area of the wall surfaces and the mean Sabine absorption coefficient (a Sab) defined as (a Sab) = Σ Ai.ai/A where Ai is the area of an individual surface characterized by the Sabine absorption coefficient ai. The total surface is A.

The classical relation for the sound pressure level in the reverberant field (far from the engine) is :

SPL = PWL - 10.log(4/A.(a Sab)) (3.6)

In ref.16 the authors recommend for the test-room with air-inlet at the forward end the following relation derived from data obtained in classical test-cells :

SPL(test-section) = PWL - 10.log(At) - C (3.7)

C has been empirically derived and is approximately equal to 6 dB for the first octave band (low frequency) and 3 dB for the high frequency octave band.

In both approaches the problem is the value of the PWL to be used. In fig.28 we show two SPL octave band spectra measured in existing test-cells (F.N. and National Research Council, Canada). Both were obtained in maximum afterburning conditions, the engine F100 in the F.N. and the J85 in the N.R.C.

With this information on SPL in the test-tunnel and allowable SPL for each source, one can determine the required wall insulation and noise absorption in intake and exhaust channels. In the case of vertical stacks the directivity losses must be considered, they will improve the sound attenuation to the receiver on the ground.

The design engineer now has to determine the wall thicknesses, the absorbing materials and the geometry of the treatment and panels (width, length, spacing etc.). This is a complicated task which requires a thorough knowledge of acoustics and an extensive documentation on available materials. This cannot be dealt with within this lecture's scope, which is essentially centred on the customer's standpoint.

A practical question can occur to the test-facility manager : "Will the noise levels at the surrounding locations be acceptable if in the existing test-cell (with known attenuation) a new engine with higher PWL is to be tested ?" A first evaluation can be reached with the help of the precedent theoretical considerations.

3.5. Measurement of the test-cell's acoustical performance.

It is the procuring agency or test-engineer's responsibility to assess the acoustical performance of the test-cell after construction and compare the measured values with the specified noise levels. The loudness level in dBA or/and the sound spectra are measured with the sound level meter in a circle the radius of which is the reference distance and the centre, the engine's exhaust orifice (or any other specified

places). Sound pressure level measurements are made at a height of approximately 6ft above ground in equal angular increments of 22.5° or less (ref.17). This high number of measurements will not always be taken but several measurements on the circle are necessary to avoid incorrect information due to the directivity effects, the sound barriers and reflectors in certain directions.

The measurements must be taken in normal atmospheric conditions. The wind velocity must be less than 8 km/h (5 miles per hour). Temperature changes can be significant as they induce noise level variations (thrust and mass flow influence) as already mentioned. An example of the results was given in fig.26.

3.6. Maximum allowable noise levels in test-section and control-room.

The procuring officer must also specify the maximum allowable noise levels inside the test-facility. We comment on the two most important criteria : first in the test-section and second in the control-room.

When the engine or aircraft is enclosed in the test-bay, the sound pressure levels on the structures are higher than in open air. The walls reflect a ce tain amount of sound energy. High sound levels can reduce the fatigue life of the engine or aircraft structures. The structural acoustic design limits may not be exceeded in the test environment.

The maximum allowable engine aft structure sound levels are given by the manufacturer and F100 example is shown in fig.29 (ref.6). By covering the test-section walls with absorbing material, the noise level can be lowered. The aft part of the test-section, opposite the exhaust, is best covered with absorbing materials matching the exhaust's frequency spectrum.

From the third octave analysis given in ref.6, we calculated the SPL spectra (octave band) for an open air test stand, a hush house and a ground run-up noise suppressor. The hush house is a sound-absorbant hangar, 25.6m by 19.8m, suitable for testing aircraft and uninstalled engines. The surfaces were covered with 975m2 of absorbing panels, 10cm thick filled with 77 kg/m3 fiberglass. The results were obtained by testing a bare F100 engine, the microphone was at 12.5cm from the engine nozzle inlet's outer surface.

In the control-room the allowable noise level is specified and given as a Noise Rating number or in dBA. If we look at fig.17 (Noise Rating Curves), specify a NR of 55 (as indicated in Table 1) and compare with the SPL inside the test-sections (fig.28), we see that a very large noise reduction is required, 50 dB in the lower frequency bands and 80 to 90 dB in the medium frequencies (1, 2 and 4 kHz). If the control-room serves as a classroom, the maximum NR could be about 35, which means a supplementary reduction in each octave band of about 20 dB.

The high noise reduction dominates the control-room's design and construction. Insulation can only be achieved with heavy walls (high mass per square meter) and separation. Anything connecting the test-section to the control-room is a potential noise transmission path. The acoustic engineer has to determine the walls' and glass panes' thicknesses and separations and to carefully design the passages for instrumentation and power cables, heating and ventilating ducts, providing these with the vibration breaks. The control-room's internal surfaces must be covered with a certain amount of absorbing material.

As an illustration we reproduce in fig.30 some NR curves and the spectra in the control-room of the F.N. test-cell with the F100 engine in maximum afterburner conditions.

The complete acoustic design problems cannot be studied in one lecture. It is at any rate a difficult problem with many approximations and physical parameters the values of which are not always well known when the project starts. Our purpose was to give the procuring officer or the test-manager an insight into these acoustic aspects in order to communicate with the acoustic design engineer, understanding his need for specific information and the difficulty of accurately predicting the performance.

I wish to thank :

- Mr. DEBECKER for revising the English text
- F.N. and BOET who provided some measurement results and authorized me to publish them.

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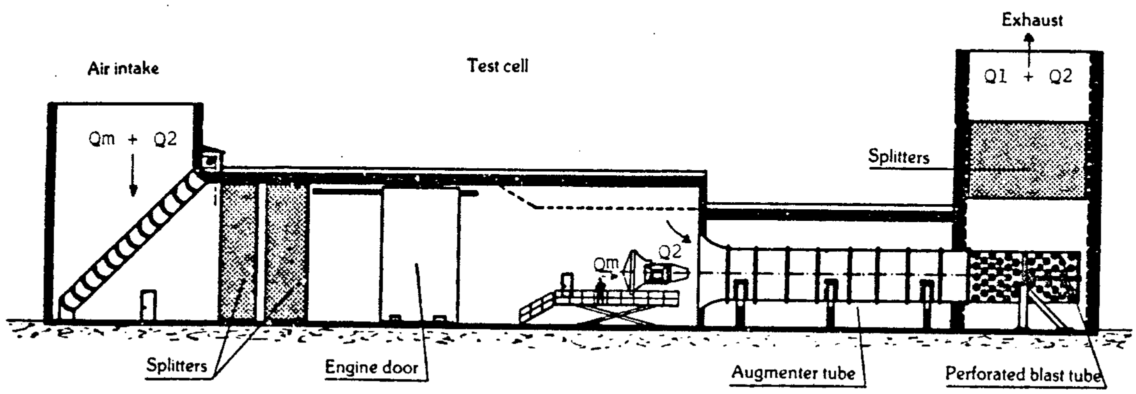


Fig 1 : AIR AND GASFLOW IN A STANDARD CLOSED TEST-CELL.

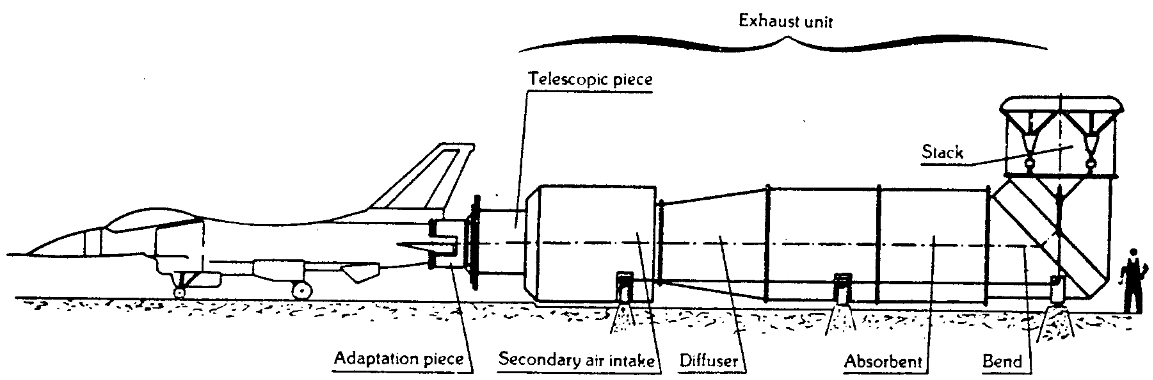


Fig 2: GROUND RUN-UP NOISE SUPPRESSOR.

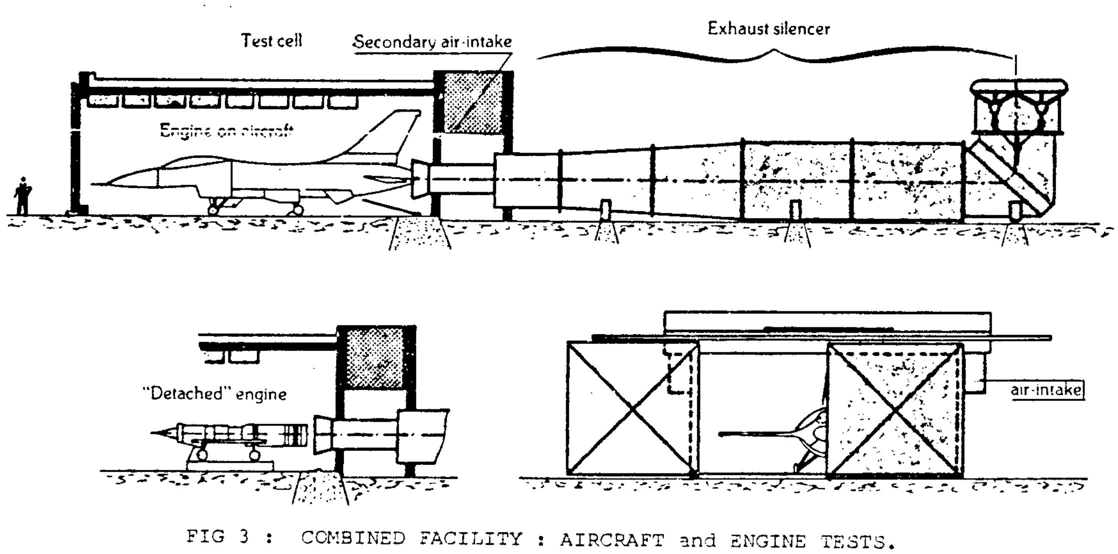


FIG 3 : COMBINED FACILITY : AIRCRAFT and ENGINE TESTS.

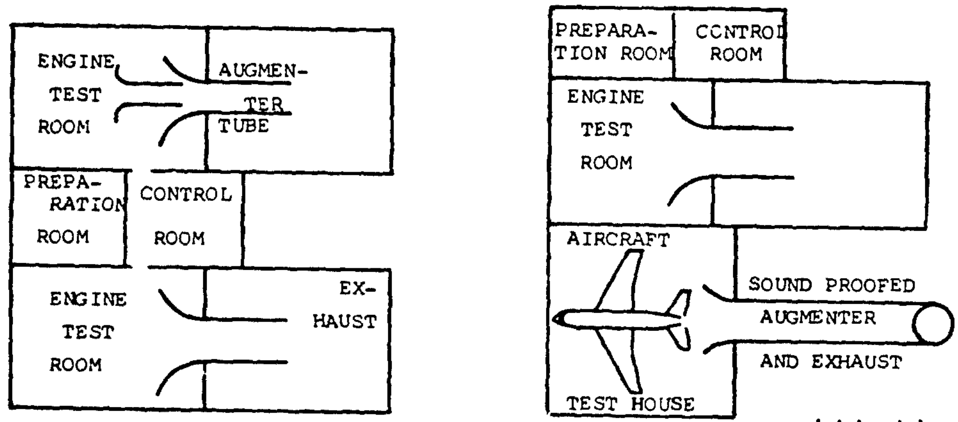


Fig 4 : LAY-OUTS OF THE TEST- BU ̣DINGS

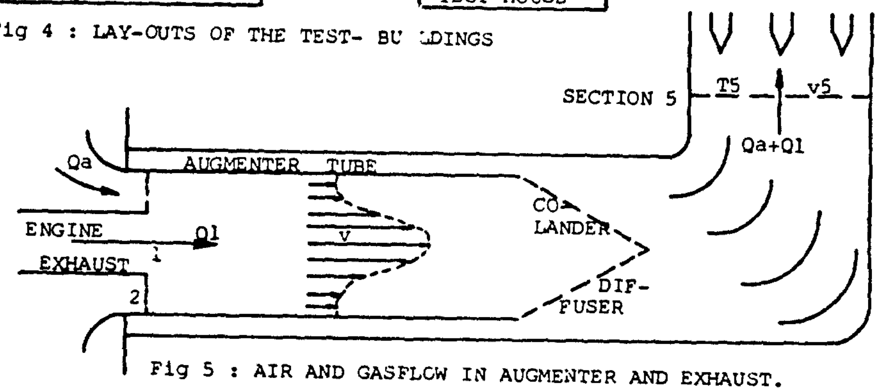


Fig 5 : AIR AND GASFLOW IN AUGMENTER AND EXHAUST.

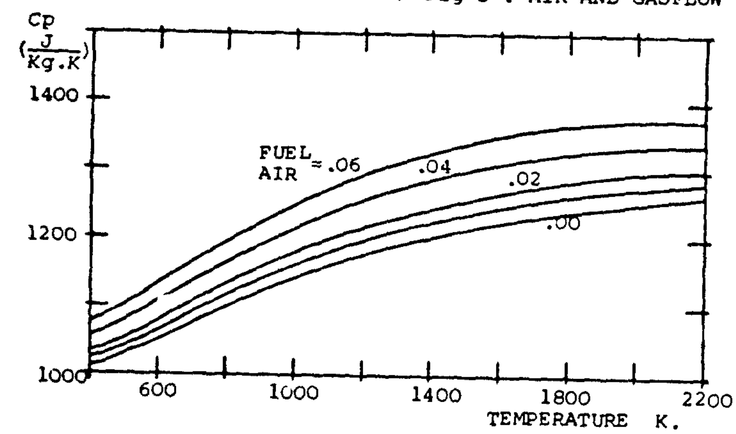


Fig 6 : SPECIFIC HEAT function of TEMPERATURE and FUEL/AIR RATIO.

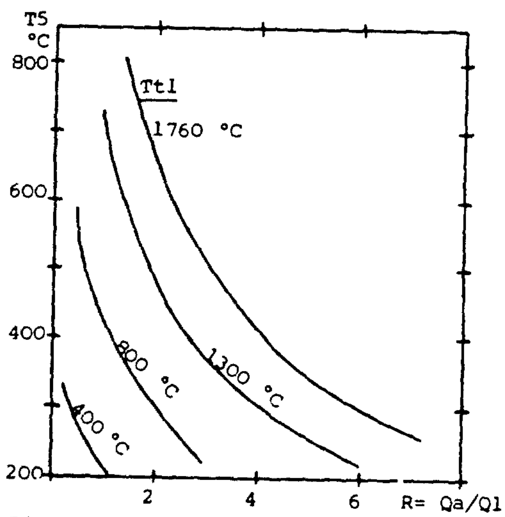


Fig 7 : MIXING T° T5 as function of R and Tt1

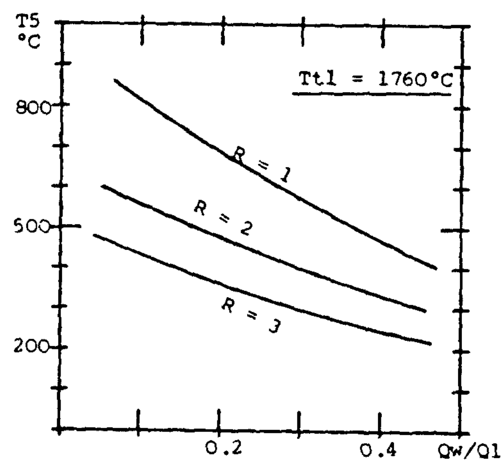


Fig 8 : WATER/GAS RATIO as f(R)

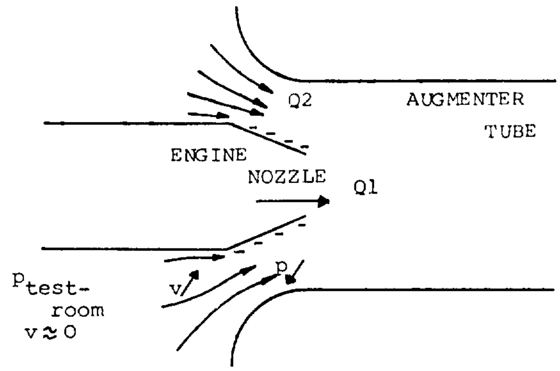


Fig 9 : VELOCITIES AND PRESSURES ON ENGINE NOZZLE

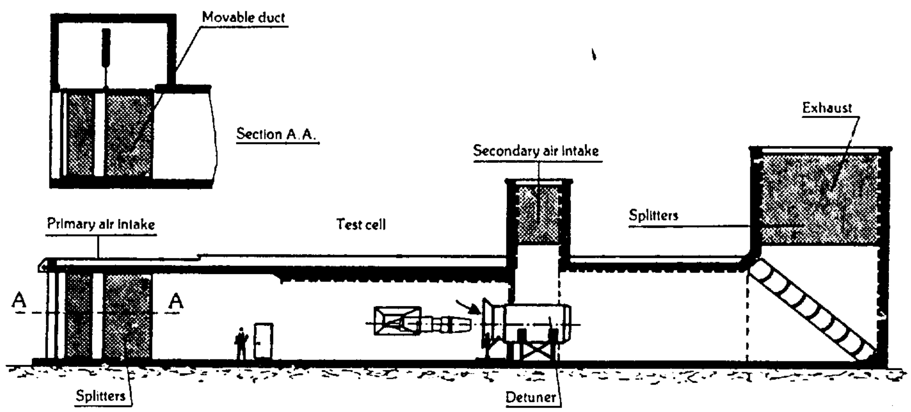


Fig 10: TESTBED with TWO AIR INTAKES and TWO EJECTORS IN SERIES

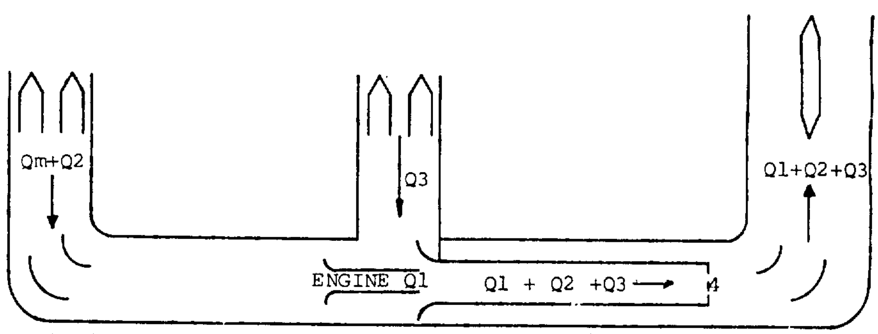


Fig 11 : TEST-CELL WITH TWO AIR INTAKES AND ONE EJECTOR

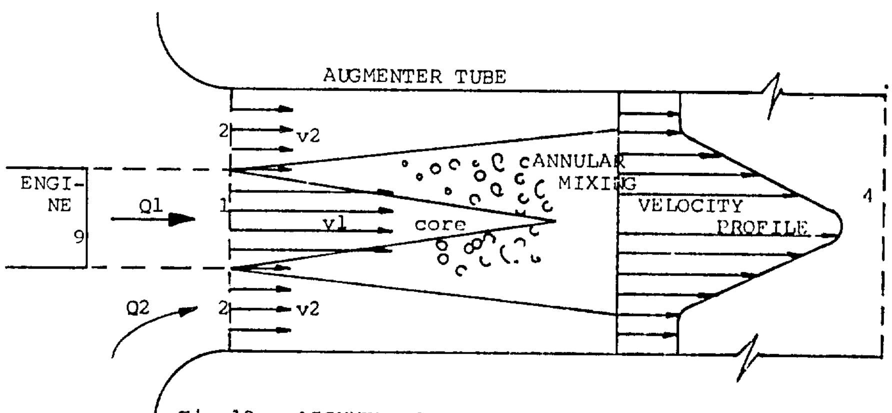


Fig 12 : ASSUMED FLOW FIELD IN AUGMENTER

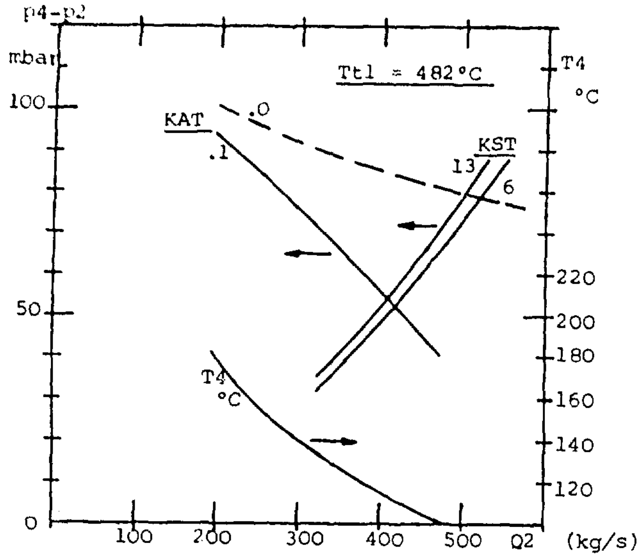


FIG 13: PRESSURE DIFFERENCES, SINGLE EJECTOR TUNNEL

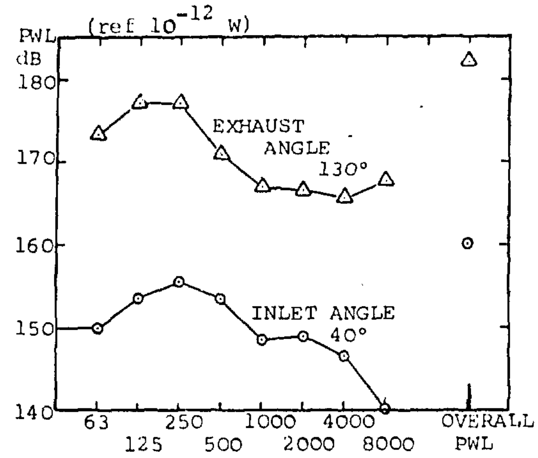


Fig 16: OCTAVE SPECTRA, free field
F 100 engine, MAX AFTERBURNING

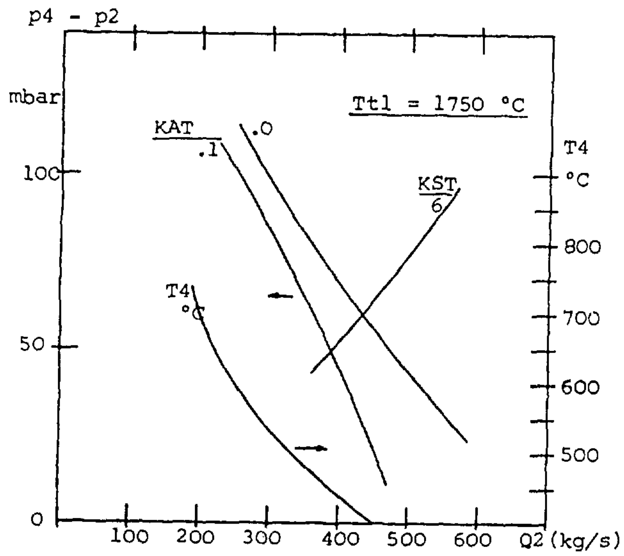


Fig 14: PRESSURE DIFFERENCES, SINGLE EJECTOR
MIL. TURBOFAN IN MAX. AFTERBURNING

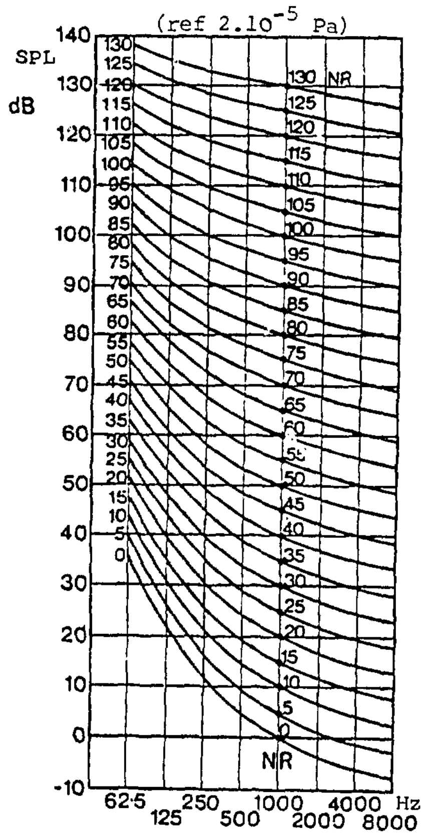


Fig 17: NOISE RATING CURVES

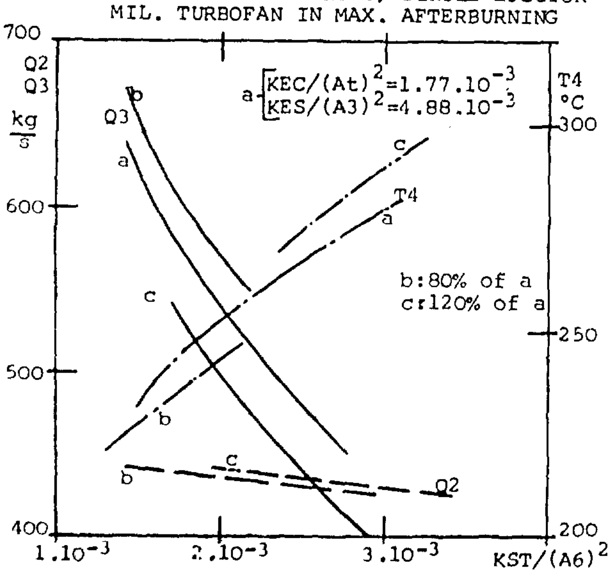


Fig 15: TEST-CELL WITH TWO EJECTORS IN SERIES
Influence of loss parameters.

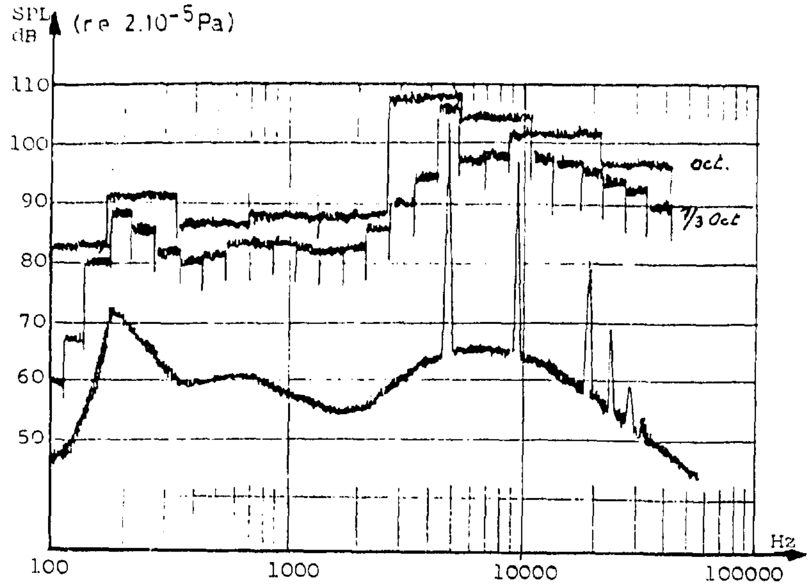


Fig 18: SMALL BAND, 1/3 and OCTAVEBAND SPECTRA of a TURBOJET ENGINE.

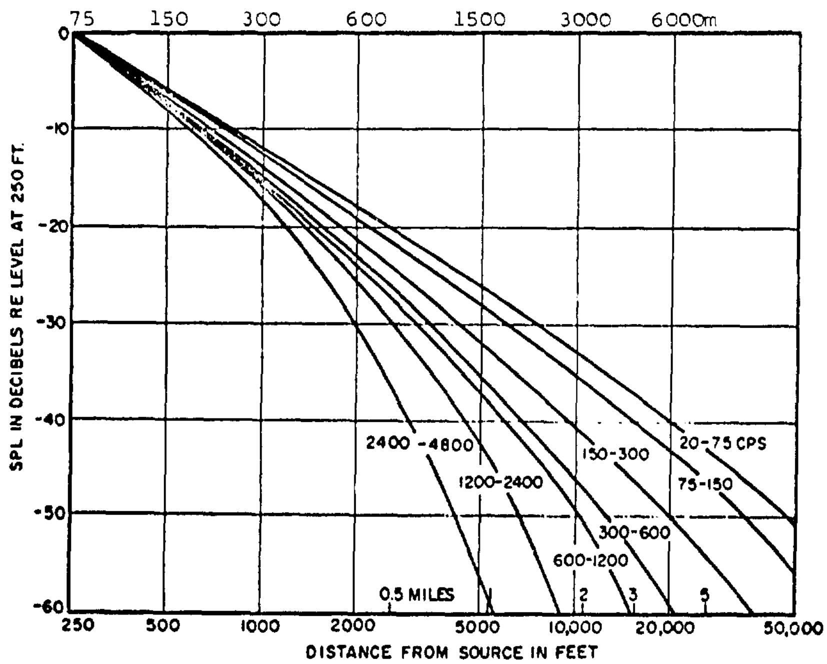


Fig 19: CONSERVATIVE VALUES OF REDUCTION OF SOUND PRESSURE LEVEL WITH DISTANCE FOR JET AIRCRAFT OPERATING ON THE GROUND

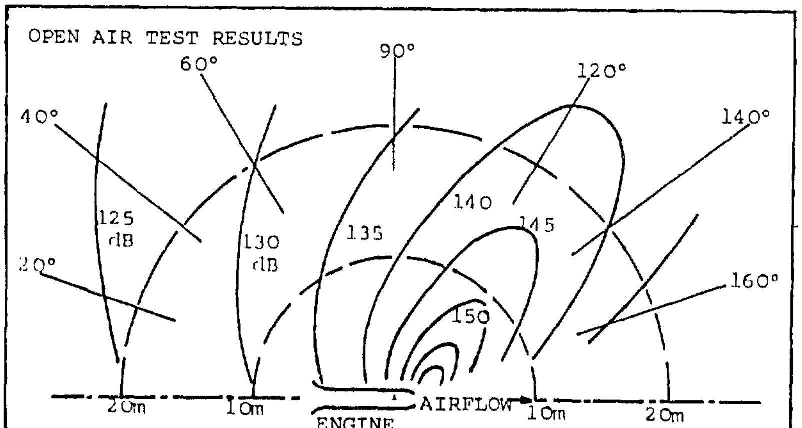


FIG 20: SPL of an F100 engine in MAX. AFTERBURNING

F-16 , STATIC
SOUND LEVEL CONTOURS
dBA

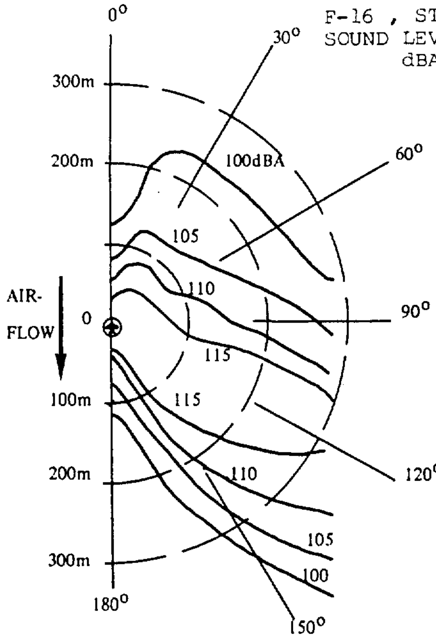


Fig 21: MAX AFTERBURNING

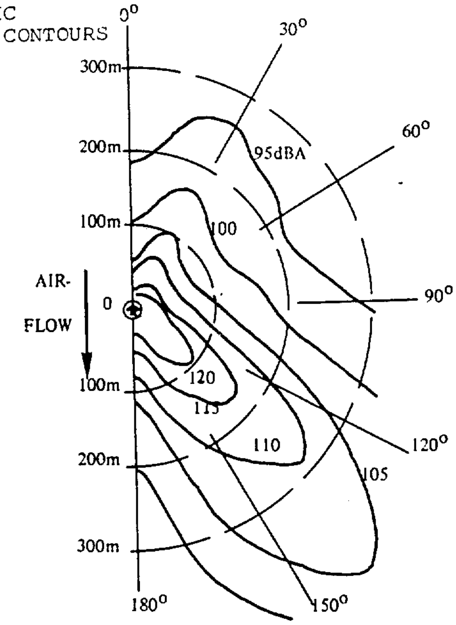


Fig 22: MAX DRY CONDITION

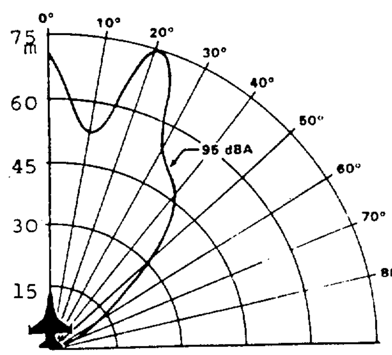


Fig 23: IDLE

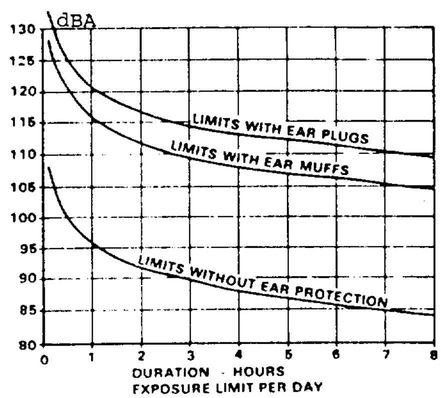
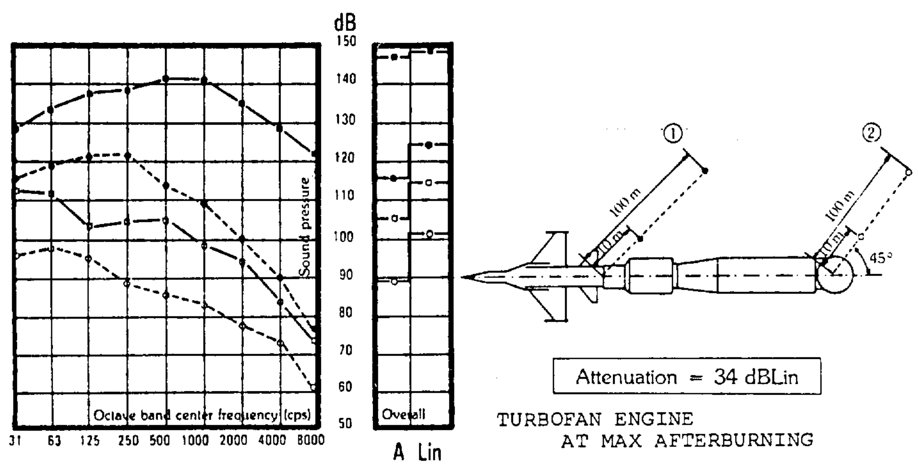


Fig 24: NOISE EXPOSURE LIMITS.



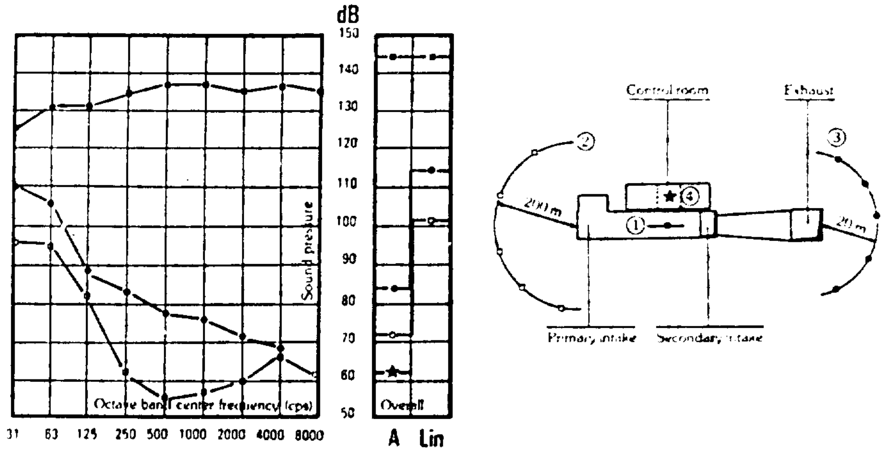
1) Without silencer —■—■—■—■— at 10 m from the engine nozzle and 45°

--●--●--●--●-- at 100 m from the engine nozzle and 45°

2) With silencer —□—□—□—□— at 10 m from the silencer's bend and 45°

--○--○--○--○-- at 100 m from silencer

Fig 25: NOISE MEASUREMENTS without and with GROUND RUN-UP NOISE SUPPRESSOR



1) —■—■—■—■— Curve: measure at 2 m and 45° from the engine, in the test cell

2) —□—□—□—□— Curve at 200 m in front of the primary intake

3) —●—●—●—●— Curve at 20 m from the exhaust stack

4) ★ Residual noise level in the control room 62 dB(A)

Fig 26: NOISE MEASUREMENTS, TURBOFAN ENGINE IN MAXIMUM AFTERBURNING

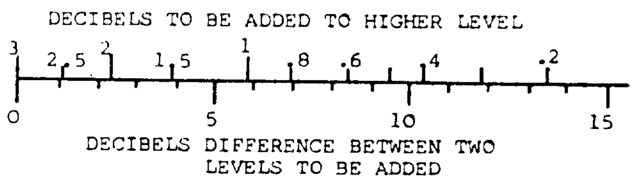


Fig 27: CHART FOR THE ADDITION OF SOUND PRESSURE LEVELS ON AN INTENSITY BASIS.

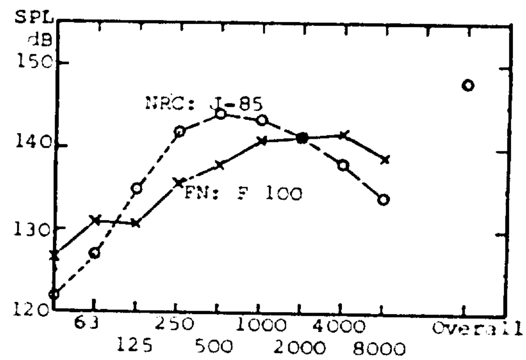


Fig 28: SPL in test-room: MAX AFTERB.

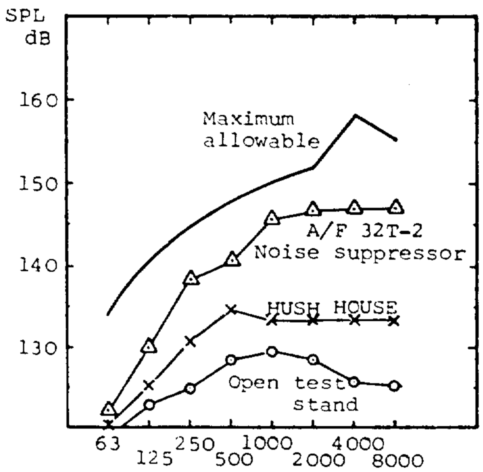


Fig 29: OCTAVE BAND SPECTRA nearby engine nozzle F-100 MAX AFTERBURNING

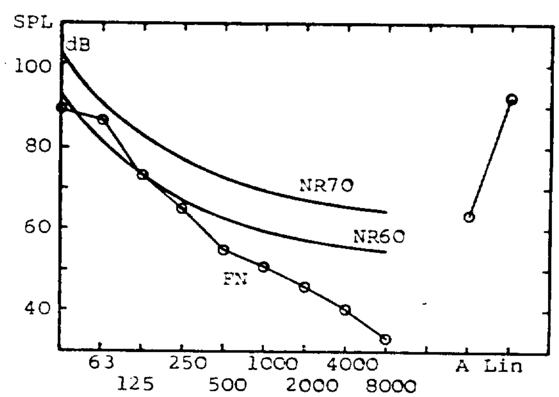


Fig 30: OCTAVE BAND SPECTRA IN CONTROL ROOM F 100 engine MAX. AFTERB.

Table 1.

Type of space	Recommended NR value	Approximate LA in dBA
Very good listening conditions (large conference rooms, small auditorium)	25	Max.42
Sleeping, relaxing zones (bedrooms, hotels, apartments)	20 - 30	34 - 47
Good listening conditions (classrooms, small conference rooms)	30 - 35	38 - 47
Moderately good listening conditions (restaurants, large offices, cafetarias)	35 - 40	42 - 52
Laboratory workspaces, small shops, lobbies	40 - 45	47 - 56
Minimum listening conditions (shops, garages, power plant control-rooms)	45 - 55	52 - 61

Table 2.

TYPICAL NOISE CRITERIA FOR DIFFERENT NEIGHBORHOOD TYPES - SPL : dB(re 2.10 Pa)								
Octave Band (Hz)	37.5 75	75 150	150 300	300 600	600 1200	1200 2400	2400 4800	4800 9600
Light Industrial	77	67	59	50	50	47	44	42
Urban Residential	74	62	53	48	44	42	38	36
Suburban	72	57	48	43	39	36	33	31
Country	67	52	43	38	34	32	28	26
Damage risk	115	105	95	85	85	85	75	90

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DEVELOPMENT TESTING - USE OF SEA LEVEL TEST BEDS AND RIGS

M.H.BEANLAND, CHIEF OF DEVELOPMENT ENGINEERING
ROLLS-ROYCE LIMITED, PO BOX 3, FILTON, BRISTOL BS12 7QE

The use of the words "Development Testing" implies a unique and well known activity which proceeds down a well known track during the evolution of an Engineering project. This is not so. The style and scale of Development can vary enormously depending on the particular Aero Engine project and the starting point. Equally the whole subject of Development itself is continually changing to meet the very severe demands imposed by economic and commercial considerations.

DEVELOPMENT PROGRAMME TYPES

Development programmes can cover the full civil certification of a brand new engine type through to the installation of that same engine into a different aircraft, or an up-rated version of the same engine, or the development of a solution to an in-service problem. All of these have very different starting points, but all are aimed at the same goal. That is the provision to the customer of an aero engine design which is fully demonstrated and validated as meeting the original specification.

Validation of the design means much more than proving the performance of the engine. It also means demonstration of airworthiness requirements as well as validating the proposed maintenance policy of the engine, and the lives of the various components within it. All of these activities require the use of a large range of Development tools and it is largely about these that I am going to talk today, and explain their use and the reasons that lie behind their use.

Let us take for our example the full certification of a brand new engine design. The immediate consideration is one of confidence level and the big question is at what point does one feel confident to commit this new engine project to a customer and hence by implication to full scale production, and how much work has to have put in before reaching that confidence level? The answer is an increasingly large amount, and very much more than would have been considered necessary in the early days of Turbo Jet Engine Development. The investment required to launch a new engine project into full scale development, and to tool-up for it's eventual production is now so large that every effort must be made to minimise the risks involved. This means carrying out as much of the validation work as possible before full project launch. I say as much as possible because there are pressures pushing in the opposite direction. Commercial considerations may force one to take more risks than one would wish in the absolute. Equally no one likes investing large sums of money in the absence of a committed customer. Hence we have the problem of maximising the upstream validation whilst minimising its cost.

This is where the design-to-cost concept becomes essential, because once a thrust range for the projected engine has been established, the designer will wish to balance the competing requirements of minimum first engine cost, minimum fuel consumption, maximum ease of handling, minimum maintenance, and maximum parts life. In the end of course the argument is an economic one, and the high cost of fuel in modern years has meant that it is cheaper overall to invest more money in a high cycle efficiency and necessarily more complex engine in the interests of low fuel usage. Hence the designer will probably wish to go for the high cycle pressure ratio and temperature and his next question is "What are my constraints?"

This immediately leads to a review of the state of the art in research and advanced development fields of a whole range of topics ranging through materials, oils, fuels, aerodynamics, thermodynamics etc. A very wide range of test rigs and equipment is used to establish and continually advance the state of these technologies and it is from this continuously moving conveyor belt that the designer extracts his current constraints and proceeds to draw down his initial design. From these designs are manufactured the first test vehicles in the Development programme. These will basically be at 3 levels, that is full engine, modules and piece-parts.

PIECE-PARTS LEVEL TESTING

Individual turbine blades will be manufactured and mounted in high temperature rigs to establish their cooling performance and thermal shock resistance. Many aspects of the turbine blade design have to be evaluated at this point. A typical modern cooled turbine blade will have a multi-pass basic aerofoil cooling system with hundreds of film cooling holes of very small diameter exiting onto the blade surfaces as well as providing additional convection cooling at the leading and trailing edges. The multi-pass aerofoil cooling is provided to ensure that with mainstream gas temperatures in excess of the melting point of the material of the blade the actual operating metal temperature is maintained at a level which gives an adequate in-service creep life. This has to be achieved in a manner which obviates large differences in local temperature anywhere across any section of the aerofoil, which would lead to internal thermal stresses which

in themselves cause excedence of the desired stress level. Finite element computer programs are used in the design of such a cooling system and have lifted the technology to a very high state, but as always, the achievement of the required balance between the external blade profile for high aerodynamic efficiency, ease of manufacture and cooling passage design leads to the need for compromise and hence the need to prove, by this type of rig testing, that the desired metal temperatures are in fact being achieved on the resultant end-product. Film cooling of the blade leading and trailing edges is needed because during engine accelerations in particular, these regions of the blade tend to heat up more quickly than the main bulk of the aerofoil and this tendency has to be counteracted to ensure a satisfactory blade life. Thus as well as using these high temperature rigs to map out the steady state metal temperatures, transient measurements are made and followed by cyclic thermal fatigue testing to further add to the confidence level in a design. This latter testing also gives information upon the durability of the anti-corrosion or thermal barrier coating that will have been applied to the blade since the premature erosion or other break-down of such a coating can negate all of the foregoing.

Compressor blades will be manufactured and tested in vibration rigs to establish their vibration characteristics and fatigue resistance. In order to prevent fatigue failures in service of blades (both compressor and turbine), it is necessary to avoid resonant conditions particularly at engine spool speeds which are other than transient. Resonant conditions typically occur where the passing frequency of an upstream or downstream set of vanes coincides with one of the natural frequencies of vibration of a rotor blade. These can be in the fundamental (or flap), torsional, edgewise or complex (ie combined) modes of vibration or indeed a higher frequency harmonic of any one of these. Computer programs are used in the design phase to predict the model patterns and frequencies of these vibrations but again to increase one's certainty of knowledge these need to be measured on the actual hardware. This is done by vibrating individual blades using a variable frequency high power exciter table and with straingauges attached to the blade at points predicted from the computer program. By viewing the blade under stroboscopic light linked to the exciter it is possible to see directly the sudden large increase in the amplitude of vibration when the blade comes into resonance. Its absolute level of amplitude will be a function of internal hysteresis and this in itself is an important piece of information since the discovery of a mode of vibration having a low damping function can in itself be cause for concern. Once having established the basic blade resonances it is our practice to carry out fatigue tests on a number of samples of each blade row wherein the amplitude of vibration is gradually increased in steps until cracking occurs. These tests are fully automated and shut themselves down on detection of an unscheduled frequency shift which signifies cracking. From our enormous background of experience of this testing and its comparison with straingauging of blades during full scale engine tests it is possible to predict with high accuracy whether a particular design will be satisfactory in service or not. If the answer is 'not' then redesign of the blade will be undertaken to either strengthen it in a particular region (maybe by an aerofoil thickness change) or its frequency maybe modified by a geometry change. Damping maybe introduced by the provision of snubbers or damping weights, or in some cases a revision of blade numbers may be considered.

A variety of rigs will be used to test shafts, casings, fuel control systems etc., in as representative environments as possible. These parts will then be brought together as modules for subsequent test on compressor rigs, turbine rigs etc.

MODULE LEVEL TESTING

It is at this point that we begin to use large scale test equipment. In order to test a compressor for example, as an individual module, we have to provide a prime mover of several thousand horse power using either large electric motors or some form of industrial turbine. Rolls-Royce possesses five large rigs with drive power of 12,000 to 18,000 H.P. and six smaller rigs used for scale model testing. The compressor is tested through its speed range, often under pre-programmed computer controlled test scheduling, measuring individual stage efficiencies and pressure ratios and its surge margin assessed. Initial optimisation of variable geometry schedules and bleed valve opening speed ranges will be established during this testing phase and strain gauges will be attached to the blading to confirm the results from the individual blade rigs. The compressor is provided with the predicted air inlet pressure profile by means of a weir plate or similar disturbance devices and very small pressure tappings are built into the compressor vanes to measure the pressure at both radial and circumferentially disposed points. The compressor outlet profile is carefully checked over the operating range and reproduced, again by flow disturbance devices, in the upstream section of the combustion rig.

Similarly turbines are driven against dynamometers using large quantities of compressed air in order to confirm their power and efficiencies. The combustion modules will be fed with compressed air at pressures, temperatures, and mass flows adequate to cover the full engine operating range and checked for efficiency, light up characteristics, rich extinction, and a very important feature, the outlet temperature profile. This of course has a very important effect upon the turbine components downstream of the combustor and may well require several adjustments before it is judged correct. In fact it is necessary to optimise two temperature profiles. The radial temperature profile is that which is sensed by the turbine rotor blading, since by its rotation it averages out the circumferential variations in temperature produced by, for example, discrete fuel injection points. It is positively not advantageous to have the radial temperature profile flat, since the stressing of the turbine blade root attachment to the disc and the tip shroud (if used) usually demand a lower temperature than the mid-span of the aerofoil.

Therefore a curved radial profile with its peak somewhere about two thirds blade height is usually optimum although due regard has to be paid to the blade cooling parameters referred to earlier in arriving at the optimum since what matters in reality is not the gas temperature at all, but the operating metal temperature of the turbine blade at any given station combined with the operating stress at that station.

The second temperature profile has been alluded to above and occurs as a thermal contour map over the total exit annulus from the combustor. It is present because of the discrete individual fuel injection points at the head of the combustor and also because of the disposition of the holes which carry the full air mass flow of the engine through the combustor walls to mix with the fuel and burn. Both this 'overall' temperature profile and the radial temperature profile are also heavily influenced by the pressure profile emerging from the high pressure compressor. The turbine nozzle guide vanes are primarily influenced by the 'overall' temperature profile and again it is necessary to optimise the balance between the air cooling system employed on the nozzle guide vanes themselves and the gas temperature profile. All of which explains why one sees such a baffling array of varieties of hold patterns in the walls of combustors on different engines, since the variation of these hole sizes, shapes and patterns is the principle way used in the Development Programme to optimise both of these temperature profiles.

It is also at this stage that any areas of the combustor showing signs of overheating are carefully tuned in order to bring the combustor skin within the required operating temperature. Modern combustors are cooled by a combination of axially injected film cooling rings spaced at intervals down the length of the combustor and localised patterns of very small holes to provide effusion cooling. 'Cooling' is perhaps a bad word to use since the objective is more to prevent hot gases inside the combustor scrubbing the walls directly, rather than to extract heat. The maximum flame temperature inside the combustor is almost twice the melting point of the material used to fabricate the combustor. In spite of this the combustor must not suffer cracking, buckling or corrosion if it is to maintain its performance and it is therefore necessary, during this rig testing phase of development, to optimise the position and effectiveness of the cooling devices along the wall of the combustor. Distortion of the combustor, particularly, can have a bad effect upon the temperature profiles discussed earlier.

The major casings of the engine will have been manufactured and then subjected to cyclic testing in massive rigid structures against which hydraulic rams can react to produce the required load. These rigs are extremely versatile and may be used to conduct tests on a wide variety of components. The casing under test will be pressurised and heated to reproduce engine conditions; loads, pressures and temperatures will be cycled under computer control and the readings automatically recorded.

A modern typical cyclic rig test of a main shaft for example will not only involve torsional and tensile applications of stress, but will also super-impose high cycle fatigue as well as pressurisation to simulate centrifugal loads and also heaters to create thermal cycling of the shaft. By these means the correct "in-engine" conditions are created and the design cycle fatigue life validated. Rigs vary in size and capacity to accommodate the range of Rolls-Royce engines, but a typical large shaft rig may impose a mean torque of 102 K Nm (900,000 lbs in.) a high cycle super-imposed torque of 6.8 K Nm (60,000 lbs in.) and a bending moment of 7.3 K Nm (65,000 lbs in.) with a typical thermal gradient of 200°C rising to 500°C along the shaft length.

SPOOL LEVEL TESTING

Since the highest cycle pressures and temperatures occur in the high pressure spool of a multi spool engine it is to be expected that most of the technical problems will exist in this area. We therefore collect together the high pressure compressor, combustor and high pressure turbine into a single spool and test this in its own right. In order to establish the correct inlet conditions the spool is placed in a closed test cell and fed with high pressure air at its inlet, thus providing those conditions which would normally come from the fan or upstream compressor. The correct exhaust conditions are produced by using steam or similar extractors to allow control of the outlet pressure. By using this plant to control the inlet and exit conditions (mass flow, temperature and pressure) we are able to fully simulate the conditions that the high pressure spool would experience if it were running in the complete engine. Obviously, by the same token we can operate the spool over its full performance carpet, including altitude operation and handling - ie acceleration and deceleration rates. Several hundred individual pressure and temperature measurements are used to assess the performance of the spool over this full range of operating conditions. This testing allows confirmation of the results obtained from the testing of individual engine modules and also tests the interactive affects of those modules. For example, "Is the carefully optimised combustor outlet temperature profile still the same when the combustor is operated behind the actual compressor as opposed to a combustion rig pipeline?" "Now that air-flows to turbine blade cooling passages are being controlled by engine-style orifices and labyrinths as opposed to easily adjustable valves in pipes - does the blade metal temperature still satisfy?"

Also we have the ability to measure those features which were not possible as modules. The level of load being taken by the main shaft thrust bearing. The rate of oil flow to the various bearings - usually provided by slave equipment on the module rigs. Oil and air system temperatures - particularly scavenge temperatures. This is also the first opportunity to match the main engine fuel control system with actual engine hardware and

check its optimisation, which up to that point will have proceeded using a full scale control system driven by electric motors and using a computer instead of an engine - a computer model which incidentally has built into it the surge lines and operating characteristics measured on the compressor rigs.

Because of the reduced complication of the spool engine relative to the full engine, more comprehensive and detailed instrument can be applied and test conditions more easily varied and controlled. For these reasons our various spool facilities are also extensively used in our research as well as development programmes.

Also built into this particular test plant is a piece of equipment that allows us to look inside the spool at any operating condition we choose. This is a very powerful X-ray machine that penetrates completely through the engine and uses either film or video techniques to establish the very important clearances between the various components inside the spool. In a modern aero-engine these clearances in themselves have a major part to play in achieving a high level of cycle efficiency and hence low fuel consumption. We have developed this equipment over the years, so that we are now able to use it in either a static or dynamic role; that is we can follow the changing clearances through the engine during acceleration or deceleration phases, and hence fully optimise those clearances which are so vital to a high performance aero engine. Also the physical movement of components inside the engine under stress can be measured to an accuracy level of 0.1 - 0.15 mm directly and by the use of image enhancement techniques on either film or video pictures we can improve the accuracy to 0.05 mm. This makes the techniques particularly useful for measuring such things as diaphragm movements under pressure and labyrinth movements under thermal expansion. By pulsing the X-ray beam and linking the pulse frequency to engine rotational speed it is possible to obtain a stroboscopic effect and view rotating parts as though they were static. Extensions of the techniques have also allowed us to study vibrating components and watch the movement of bearings upon their squeeze-film housings. The beauty of this technique is that it requires no extra instrumentation to be fitted to the engine and no special build of the engine. As such it is completely "non-invasive". Other techniques that we have developed that are equally non-invasive include the use of neutron beams to examine the movement of oil and fuel within the engine. Infra red to examine external temperature patterns and holography to study the vibration of blading. As well as investigative work we also use these high pressure spool plants to carry out endurance tests and cyclic tests.

FULL ENGINE LEVEL TESTING

Now we come to the testing of the complete engine, and perhaps you ask why we did not put the whole engine together to start with. Well, as I said earlier it depends upon one's level of confidence and the amount of new ground one is breaking. In some Development programmes one would indeed start with the complete build of an engine, but only where one had sufficient background to enable that to be a confident starting point.

A typical sea level engine test bed will be provided with enough cross sectional area to give an air flow through the bed of about 20 ft per second, and an inlet to give a smooth flow of air into the engine. The test bed will be provided with means of loading the hydraulic pumps on the engine and the electrical alternator. Also provided will be a range of measuring equipment to cover some fifteen hundred plus parameters of steady state, transient, and dynamic information. The difference between these various terms is one of rate of acquisition; at the dynamic end going up to hundreds of samples per second. Some of the test programmes to be carried out on this bed will be fully automated, particularly for example simulated mission endurance tests where many of the signal inputs that would normally come from the airframe, such as the requirement for hydraulic and electrical loads and the start of a water injection phase, are supplied automatically from the test bed equipment.

All performance parameters on these beds are gathered electronically, complete with individual correction factors and calibration curves applied prior to the calculation of the engine performance and with read-out of corrected data at terminals in the engineering department to enable decisions to be made whilst the test is in progress. Also all beds are land-line linked to central mainframe computers for further detail analysis of the engine performance. Up to a thousand parameters can be measured within 60 seconds and automatic arrangements are made to monitor readings against a known reference to ensure consistant accuracy. To collect data on command, an automatic scan of the instrumentation at the rate of 1000 parameters per minute is initiated. A typical scan will display a pre-arranged selection of up to 32 parameters on a monitor screen in the test house control room 3 seconds after the scan is completed, while the computer continues to process the data to analyse the engine performance. For transient condition recording a rapid scan facility allows up to 128 channels to be scanned per second. This is of considerable value in determining engine behaviour, but for more detailed investigation of dynamic conditions, continuous recording is used. Signals are recorded on magnetic tape for subsequent analysis and for immediate read-out ultra-violet recorders can display traces directly. Current advances in instrumentation technology are improving these facilities still further and Rolls-Royce operate a policy of continuous investment in this field.

The wide range of the current Rolls-Royce commercial and military engine spectrum necessitates the provision of a corresponding range of test facilities. With over 130 test cells and open-air facilities worth over half a billion US dollars, we are equipped to carry out testing of all kinds, on any turbojet or turbofan of up to 70,000 lbs of thrust including the ability to test vertical thrust conditions on vectored-thrust engines.

We also have the capability to test turboprops and turboshafts up to 7,500 H.P. However, in a modern development programme much more than straight forward endurance and performance work needs to be carried out on the engine prior to certification. For example when the engine is installed in the air frame it will have an intake in front of it and these set up their own distortion patterns of the air entering the engine. These distortions are established by calculation and by model tests of intake models, and the distortion is then simulated on the full scale engine by the use of bias gauzes. These are overlapping sheets of gauze set up in patterns which will have been established from the model test work and fully simulate the distortion effects of the actual intake, which in the case of a sharp-lipped supersonic intake can be quite severe at high angles of attack. These are then placed at the engine inlet face and the engine tested to establish any effects on things like surge margin, engine performance, and compressor blade vibration. This testing is usually followed by actual flight test strain gauging of the front rows of blades in particular and for example on Concorde over 400 test flights included strain gauge testing, covering all four intakes. All four were tested because whilst the aircraft is a mirror image port to starboard, the engine rotational sense is constant and particularly on a supersonic intake this gives rise to very different distortion patterns on the intake airflow from port to starboard.

During its service life the engine will also be called upon to swallow things that are not always to its liking. For example, birds, hailstones, ice rods, sand etc., and these all have to be tried out whilst the engine is on the sea level bed. Since many of these objects are ingested at high speed it is necessary to provide large barrelled pneumatically powered guns to shoot birds and hailstones etc. into the engine whilst it is running at full power. Very high speed cine-cameras are used to observe the effects of these tests as well as the normal instrumentation.

It is sometimes necessary to provide heated air at the inlet to the engine, either to test the effect on engine performance of hot day take-off, or in the case of supersonic engines, to simulate the effect of cruise operation at Mach numbers over 2 which means providing air at temperatures as high as 150°C. In the case of hot day take-off simulation we use the compressed, and therefore heated air which would normally be used in a turbine rig or the Altitude Test Facility, and mix this prior to the test house inlet splitters from whence it is naturally drawn into the intake of the engine under test. For supersonic engines we either use the ATF itself or attach a pre-heater to the front of the engine and burn fuel in this stream, using the natural suction of the engine to draw air through the heater.

The sea level test bed will also be used for checking out design margins; typically on turbine inlet temperature and also spool overspeeds. These tests are not only of great confidence building value but can also indicate where greater than expected margins occur and thus lead to uprating possibilities.

To check that the noise levels of the engine are within specification we have to move to an outside test bed, since various reflections from the sea level bed wall would confuse the results. Last year Rolls-Royce commissioned its most modern Noise Test Facility allowing open-air testing of engines up to 80,000 lbs thrust well clear of the ground. The whole test site is remotely controlled to remove the interference of buildings and the test bed itself can be rotated about its axis to vary the axis of the engine relative to any wind direction. This site is also proving very useful for 'free-stream' performance testing of engines, obviating the need to allow for test cell depression.

We also use external test beds for establishing the effects of reingestion of exhaust gases on vertical take-off engines like Pegasus. Although this effect is not very marked on the current Pegasus in hover, since the forward nozzles use only low temperature fan air, it will be more so in the future when it is expected to reheat this fan air, and for this reason a complex test centre involving a complete aircraft on a vertical moving cradle has had to be built, in order to demonstrate the method of solving this potential problem.

Engines have to operate over a wide range of angular attitudes, and in these cases it is necessary to test that the oil system in particular can continue to maintain an adequate supply when the engine is at extreme angles. Again, test beds capable of running an engine at angles up to 90 degrees are used.

INTEGRITY TESTING

All of the foregoing of course lies in the regime that we have described as validation of the design. There remains a long list of integrity or "what if" questions. Typically these will include, What happens if the engine runs out of oil? What happens if a fan blade fails at the root, or a turbine blade? Although all of these will have been designed not to happen, these questions have to be addressed and in many cases proved by actual test. This is sometimes the case for blade off failures, and here we insert an explosive charge into the blade root, run the engine up to full operating speed and then deliberately fail the blade by means of the explosive charge. Under these circumstances it is not expected that the engine will continue to operate satisfactorily of course, but there is a firm requirement that all of the debris shall be contained within the engine carcass and therefore not provide a hazard to the aircraft. Discs, both compressor and turbine, represent a particular case since, although much work was done in the past to establish how turbine and compressor discs could be contained in the event of failure, it was shown that the extra weight required to provide this containment

was totally uneconomic. Therefore, the practice for many years has been to establish a safe life for these components at which they are changed, well before any significant likelihood of failure is apparent. In order to establish the validity of this on individual components, extensive cyclic fatigue tests are carried out using cyclic heating and cooling where relevant, and also very detailed finite element stressing is carried out to establish that even in the presence of a small defect, a satisfactory life will be achieved from these discs.

TESTING PHILOSOPHY

During all of this full scale engine testing it is our practice in Development to operate, maintain, overhaul and repair development engines as closely as possible to those same practices which will be used by the customer. Obviously there are circumstances when a part is specially instrumented or particular types of test when this philosophy is not possible, but we have found it much to our own as well as the customer's advantage to try to stick to this philosophy. Many years ago it was common practice to completely strip engines following endurance testing in order to carry out a detailed examination of all the parts. Whilst this is still done for certain specific tests it is now more the norm to treat the engine on an "on-condition basis". This means that we use the standard customer methods of boroscope inspection, oil analysis (both magnetic chip and spectrometric as well as chemical analysis), vibration monitor read-out, performance trend analysis etc., as the indicator of the health of the engine. Using this method, engines often go on to carry out some other part of the test programme without strip and even when a strip becomes necessary, it is likely that only the affected module will be changed. Parts requiring repair are then salvaged utilising the techniques expected to be employed by the customer - which sometimes involves having a knowledge of the customer's capabilities and capital equipment availability.

This same philosophy is applied with respect to the air crew. When a deliberate failure test is being carried out for integrity checking, it is assumed that there may be a gap of as long as 15 seconds between the air crew receiving a red (immediate action) warning signal and actually taking the action (to shut-down the engine for example). Thus, in the test itself, the engine is left for this time after receipt of the warning signal, before action is taken.

In the case of the brand new engine that we are discussing, these full scale engine tests will have accumulated something in the region of 4,000 test hours by the time the engine is certificated as suitable for service, but the Development programme will not stop there. It is traditional to fund Development for at least the first two years of in-service operation, partly to cover those problems which arise in service, but which have not been uncovered by the Development programme and partly to allow further development of those areas of the engine which will have been found to contain more than adequate margin. For example it may be possible to improve the engine performance in some areas relative to the original specification, or it may be possible to reduce the cost of manufacture of certain parts of the engine. In some cases the in-service operation differs from that which was assumed at the start of the programme, particularly in the case of a military application where the recognition of a changed threat may require a change in operational usage.

However, it will be obvious that it is the full scale engine development part of this programme that consumes the greater part of the cost, using as it does sizeable quantities of fuel and consuming development hardware. For this reason a continual pressure has been maintained over the years to force as much of the knowledge gathering work as possible, upstream of the project launch and commitment point. This, in turn, forces the need for the ability to gather more information and hence confidence level more and more cheaply. I am sure this will be a continuing activity. It continues to represent the biggest challenge still to the practitioner of the development task.

INSTRUMENTATION TECHNIQUES IN SEA LEVEL TEST FACILITIES

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SUMMARY

This paper describes the application of instrumentation used during testing of turbojet and turbofan engines in sea level test facilities. The operating principal of various transducer types are discussed along with errors encountered and techniques used for calibration. A brief description of systems used for data acquisition, monitoring of engine health, and ensuring safety of the engine under test is also presented.

It is the intention of this paper to present general information in the application of instrumentation devices and systems for the benefit of individuals with limited experience in the field of instrumentation. It discusses some, but by no means all, of the measurement techniques practiced in the engine development process. A selection of references is provided for those interested in reading further.

INTRODUCTION

The requirement for engine testing comes about from the need for information concerning one or more characteristics of an engine under investigation. The role of the measurement process is to transfer this information from the engine to the user. The basic component of all measurement systems is the transducer, a device which changes energy from one form to another. Variables such as pressure, temperature, position, etc. are detected and converted to an electrical signal for further processing and conversion to engineering unit data.

The need for planning in this process cannot be over emphasized. Planning begins when requirements for specific tests are identified. Planning is an iterative process between instrumentation, test, and performance personnel to determine if stated test objectives can be obtained to the required accuracy using available instrumentation techniques and systems. If sufficient accuracy cannot be obtained, test objectives must be changed or test delayed until instrumentation of adequate accuracy is acquired. Frequently there are strong, continuous pressures for rapidly running tests and minimal emphasis for valid data. Too often data is assumed to be good, and then the most important objective becomes running the test. This is a grave error in logic.

Once the purpose of a test is understood and instrumentation identified, a thorough check of every important measurement must be made. Reasonableness checks, during the initial engine run or soon after, should also be made. Is air flow reasonable? Are fuel air ratios or engine speed about what is expected? If problems or questionable areas develop they should be analyzed and corrected before a test is continued. Remember, the purpose of engine testing is to obtain information and questionable data negates the test objective. Unless effort is made to eliminate problem areas before a test the cost of retesting will exceed the cost of checking. The technique of obtaining valid data can be summarized very easily; check, check, and recheck. Check transducers for proper installation. Check calibration data. Have environmental effects of transducers and signal conditioning equipment been considered? A measurement system is composed of many sub-systems, each interfacing with the next. It's obvious that it can be no better than its weakest sub-system. This lecture will describe instrumentation techniques used to obtain engine performance information as well as ensuring engine safety during testing in sea level facilities.

TRANSDUCERS FOR PERFORMANCE MEASUREMENT

FUEL FLOW MEASUREMENT

Fuel flow measurements are normally made using turbine type flowmeters. These have an axial flow, multi-bladed free spinning rotor driven by the velocity of the flowing liquid. They are designed so that the rotation of the rotor is linearly proportional to the flow velocity, hence the volumetric flow. The speed of the rotor is detected by an electromagnetic probe which senses the passing rotor blades. Each pass-

ing blade generates an electric pulse resulting in a frequency that is a measure of flow. The electromagnetic probe creates a drag on the rotor, especially at low speeds, causing a smaller range of linear operation than is sometimes desired. For some applications it is necessary to use a large meter in parallel with a smaller meter and a valve to select one or the other in order to get adequate range.

Some of the newer meters have a similar sense probe; however; it is excited by a high frequency oscillator. The passing blades modulate the high frequency signal which, after demodulation, generates a series of pulses similar to the output of the electromagnetic probe. These are called modulated carrier type meters. They offer a wider flow range than the permanent magnet type due to the elimination of the magnetic drag. Nominally, turbine meters have an accurate flow range of 10 to 1 or better, allowing it to operate satisfactorily through the engine operating range.

Uncertainty of the fuel flow measurement depends upon calibrations of the flowmeter and on the fuel density measurement, both of which are dependent upon accurate temperature measurements during calibration and operation. The working flowmeter is calibrated at 10 or more points over the operating range against a reference standard turbine meter with the meters in series in a straight section of pipe. Another uncertainty in use of turbine meters, particularly small meters, is that they are viscosity sensitive. They should be calibrated on the same type of fuel as used by the engine to minimize this effect. With proper temperature measurements and density corrections the result is a working meter calibration, which is within +/- 0.5% of the volumetric flow over a specified operating range.

Normally, test stand flowmeters are in the low pressure fuel line to the engine. If flowmeters are installed on the high pressure discharge side of the engine fuel pump, as is common on flight engines, several additional variables are introduced. The fuel is compressed measurably, requiring a density correction. The meter body expands due to higher fuel temperature by a calculable amount, requiring another correction.

The flowmeter measuring total engine flow is calibrated with its individual flow straightener sections, both upstream and downstream, and should not be used without them when installed in a test stand. In the upstream section is a thermocouple which is used during meter calibration and must be kept in good condition. Turbine meter calibrations can also be affected by dirt or lint in the flow path so flowmeters should be capped when not in use and kept clean at all times. Engine stands usually have two permanently mounted flowmeters for redundancy. These are connected to preset counters in the control room to indicate a nominal mass flow and also go to the data acquisition system.

Mass flowmeters, based upon inertial properties of the fluid, are used in some aircraft to keep account of fuel burned and fuel remaining. They are much more complex mechanically than turbine meters, cost much more, but eliminate the problem of measuring fuel density in flight. They may be used in test stands for special tests to determine correlation between test stand and flight installations. However, their accuracy is inferior to that of a properly corrected turbine meter. Turbine meters are known to be dependable flow sensors with low pressure drop and, when properly sized and installed, have an overall measurement uncertainty of approximately +/- 1%. Costs are near $1000 per flowmeter.

TEMPERATURE MEASUREMENT

Most temperature measurements, are made with thermocouples. Chromel-Alumel, type K, is generally used for measurements up to 2000°F and Platinum-Platinum/Rhodium, type B, is used for turbine temperature measurements up to 3100°F. There are periodic suggestions to use Copper-Constantan for inlet temperature measurements. A disadvantage is the very high thermal conductivity of the copper leg. This causes heat conduction errors which counteract any possible advantage.

The thermocouple appears deceptively simple. Actually, it presents some very complex electrical and heat transfer problems in application, so that getting accurate data is not simple. First to be noted is that the output of a thermocopule is a measure of the temperature difference between the working junction and a reference junction. The temperature of the reference junction must be known, and any uncertainty in knowing that temperature must be added to other uncertainties in the system. One way to keep a reference junction at a known temperature is to immerse it in a container of crushed ice and water which, if done correctly, can be safely assumed to be at 32°F.

Another approach is to allow the reference junction temperature to drift with ambient temperature. Most large capacity temperature measurement systems use a version of this idea. A multiplicity of thermocouple leads are terminated in a Uniform Temperature Reference, (UTR). Each termination is on a pair of copper blocks. A matrix of

such copper blocks is assembled so as to be nearly isothermal as possible, but electrically insulated from each other. The assembly of blocks is put inside a heavily thermally insulated box to minimize thermal gradients in the assembly. The thermoelectric voltage generated by the temperature difference between the measuring junction and the reference junction (at the copper blocks) is transferred from the UTR to the measuring instrument by copper wires. The temperature of the UTR block is measured using two or more pairs of copper blocks as measuring junctions in thermocouple circuits having automatically maintained ice junctions. As a minimum, two such thermocouples are used, one at either end of the matrix of blocks to monitor any unwanted thermal gradients. A properly working reference junction thermocouple operating with an ice point monitored UTR should have an uncertainty not greater then +/- 0.2 °F up to about 500 °F. To obtain this accuracy the following precautions must be followed:

- o Use of a single length of calibrated thermocouple wire from sensing junction to UTR.
- o Protection of the UTR from severe blasts of hot or cold air in order to limit thermal gradients to about +/- 0.1°F.
- o Use of single lengths of calibrated thermocouple wire as reference thermocouples between the UTR and automatic ice junctions.
- o Assurance of properly operating automatic ice junctions, by frequent comparison of data from the two or more junctions used.

One reliable, accurate method of automatically maintaining an ice junction is to use an ice point reference instrument. This instrument maintains the reference cell at 32°F with a max error of +/- 0.1° F. The reference temperature is established by the physical equilibrium of ice and water, sustained by an automatically controlled thermoelectric cooler, within a sealed unit.

Metal temperatures are also usually measured by means of thermocouples. Very small thermocouple wires are desired for best definition of the measuring point; however, larger wires may be more durable and stable. To be sure that the junction reaches the temperature of the metal it is convenient to tack weld the wires to the surface, but this is unacceptable on highly stressed parts. Thermocouples are calibrated by immersion in a liquid bath or calibration ovens whose temperature is determined using reference standard thermocouples. Calibration uncertainties of +/- 0.5°F can be achieved at temperatures below 300 °F and +/- 2°F up to 2000°F

THRUST MEASUREMENT

Thrust measurements are dependent upon the proper performance of the thrust bed facility and the force measuring load cell. The engine is mounted on a platform or thrust bed flexibly mounted for movement in the axial direction but rigid in all other directions. Most recently constructed stands have the thrust bed hung on four or more hangers made flexible in the axial direction by plate-type steel flexures. The actual forward motion of the flexure suspended thrust bed is restrained by a measurement load cell which is very stiff. The load cell is carefully designed to be accurately sensitive to axial loads and less sensitive to off-axis loads. The load cell contains two or more independent strain gage resistance bridges which are recorded by the data system, and can be switched to a digital volt meter for displaying thrust indication to the test stand operator.

Calibration of the thrust measuring system is provided by a calibration load cell, similar to the measurements load cell, but located with a hydraulic jack at the opposite end of the thrust bed. The calibration system must not be mechanically connected to the thrust bed during engine running. When a calibration is to be performed the calibration load cell and jack are connected to the thrust bed. A simulated thrust load is applied by the jack in series with a calibration load cell, thrust bed, and measurement load cell. A twelve or more point calibration is made over the working range of the stand, first with increasing load, then with decreasing load. Analysis of calibration data and comparisons with past calibration data reveal any non-linearity and hysteresis introduced by the thrust bed suspension, engine plumbing, or other factors.

If the thrust bed is working properly it will have negligible hysteresis and non-linearity. If these are not acceptable, then the thrust bed or engine mounting must be investigated and the problem corrected so that a satisfactory calibration can be obtained before running a test to determine engine performance. Typical problems encountered are: Mechanical interferences between engine mounted hardware and a fixed member of the stand; a loose nut or other object falling into a crack between moving bed and fixed structure; or restraint of motion due to pipes, wires, tubes, or other items crossing the gap between the moving bed and fixed structure. Additionally, a discrepancy between either bridge in the measurement load cell indicates mechanical trouble in the load cell.

The thrust calibration from one engine installation to another in the same stand should not vary more than +/- 0.3% of full scale. The effect of this bias shift upon thrust data is eliminated by always calibrating after mounting, just before running, and calibrating again at the conclusion of a run to prove that nothing has changed. Aerodynamic pressures on the engine are potentially a larger source of error than the measuring system biases noted above. Momentum corrections of inflowing air and bouyancy corrections from pressures acting on engine external surfaces and bellmouth must be made. These corrections can be derived analytically from flow and pressure data.

The calibration load system with its cable and electronics should be periodically returned to the calibration laboratory to be checked against a reference standard load cell to verify its stability. A multi-point calibration is made within the full range of the load cell. The uncertainty of the calibration process is within +/- 0.2% of full scale. Load cell costs are approximately $3,000.

PRESSURE MEASUREMENT

Pressure measuring systems usually consist of sensors in the flow passage, tubing conducting the sensed pressures to transducers where pressure magnitude is converted to electrical voltage, and a recording system which stores or displays the data. Components will be discussed in that order. Steady state pressures are usually sensed by static taps or from total pressure pitot tubes facing the air stream. Static taps are common in aerodynamic and flow measurements. Obtaining a true pressure from total pressure pitot tube becomes more complicated. If flow direction is known not to change over the range of conditions of test then a single pitot tube will suffice to get total pressure measurements. In most cases the flow direction is not known within a wide angle, so a short section of thin wall tubing is placed concentric with the impact tube. This device is known as a pressure Kiel head. This will improve the acceptance angle from +/- 10° to +/- 30° without exceeding 1% error in total pressure measurement. Pitot-static probes are used to measure total and static pressure simultaneously.

Beyond the sensor, the next element is tubing connecting sensors to transducers. In most steady state pressure measurement systems the accuracy demands require that transducers be protected from temperature changes. Thus, they are in an air conditioned room, even possibly in a temperature controlled box. Hence, the pressure lines are frequently very long and should be periodically checked for leaks, flow restriction, kinks, or dips which can trap liquid.

The transducer is the next item in the pressure measurement system. Present systems use very stable strain gage pressure transducers, closely coupled to a multichannel rotating scanning valve and are temperature controlled within +/- 2°F. Within each data scan are a vacuum zero-pressure reference and a near full-scale pressure reference. With this on-line calibration the pressure transducer only has to remain stable for a very short interval between calibration recording and pressure recording, resulting in an output that is within +/- 0.1% of full scale.

The final item is the recording system which, under computer control, samples the output of all pressure transducers, thermocouples, and other channels. It is chosen with adequate resolution and stability and calibrated on-line against an electronic reference voltage. The entire pressure measuring system, exclusive of the sensor calibration, has an overall uncertainty of +/- 0.1% of full scale.

Dynamic pressure measurements have different requirements than steady state pressure measurements. Usually the frequency content of a pressure signal is the important information. As in steady state pressure systems, the dynamic pressure system has a sensing port, coupling tube, transducer, and recording system, all contributing to the frequency response of the system. In order to get uniform response over the frequency range of interest it is usually necessary to reduce the coupling tube length to a minimum, locating the transducer as close to the sensing port as possible. This is because the column of air in the sense line can vibrate similar to air in an organ pipe distorting the data being recorded. In the extreme, for very high frequency data, flush diaphragm transducers may be used exposing the transducers sensitive element directly to the cavity where pressure fluctuations are to be measured. Two types of pressure transducers are used routinely. One type operates on the principle of a piezoelectric quartz crystal which has a high natural frequency and is capable of operating at 500°F. However, it is vibration sensitive so when used in an unknown vibration environment a check run should be made with a pressure port blocked off to determine the vibration component of transducer output signal. The second type operates on the principle of a semiconductor strain gage. It also has a high natural frequency but is limited to 350°F. Application of these transducers frequently involve attaching them to an engine case or engine control component. As a result, the semiconductor type transducers are more frequently used in spite of the need of water cooling assemblies. Dynamic pressure data is usually recorded on magnetic tape recorders. Transducer calibration is accomplished by applying known static pressures over the full range of the transducer at several stabilized temperature conditions. Using reference standards, the uncerta-

inty of the calibration process is less than +/- 0.1% of set point. Cost of dynamic pressure transducers is approximately $500 each.

AIRFLOW MEASUREMENT

Airflow measuring devices are used when determining compressor bleed airflow for such applications as cabin pressurization and anti-icing at the engine inlet. Measurements are affected by many variables including: inlet and discharge pipe sizes, location of pressure taps, flow distortion or swirl from upstream or downstream departures from a straight pipe, turbulance, pulsation, and air density, humidity and viscosity. Sometimes all of the variables are not well controlled, so their effect on accuracy should be determined by a person knowledgeable in these effects.

One requirement of flow measuring devices is that they create minimum pressure drop. As a result, the signal generated between the two pressure taps is usually so small, perhaps a few inches of water, that it creates measurement accuracy problems. The pressure taps must be made to specifications, and when in a region with significant flow velocity, they must be in a smooth surface and free of burrs. Pressure lines must be kept leak free and run so as not to trap liquid from condensation or otherwise. Pressure transducers should be carefully selected and well maintained.

Critical flow venturis provide the most accurate available means of measuring air flow. They have the requirement that enough pressure drop be expendable to achieve sonic velocity at the throat. At pressure drops greater than this value the flow is independent of downstream conditions. The uncertainty in the flow coefficient has been shown by calibration and analysis to be +/- 0.1% of point.

Sharp-edged orifices are the most common general purpose air flow measuring devices as they are cheap, easily made, and easy to install. Orifice plates have the metering hole sharp on the upstream surface but usually beveled on the downstream surface. The metering hole must be kept free of nicks and burrs and the upstream orifice plate surface be clean and smooth. Orifice plates designed to ASME or ISO specifications will provide a measurement uncertainty of +/-2% of point and not much improvement can be expected by calibrating as there are too many uncontrolled variables affecting the results.

Airflow into an engine is calculated from known bellmouth characteristics and measurements of inlet temperature, inlet total pressure, inlet static pressure, and ambient barometric pressure. The value of inlet total pressure is slightly below barometric pressure due to the pressure drop across the inlet screen. This is calculated by using the inlet total pressure probe and a low range differential pressure transducer with one side vented to ambient. Barometric pressure is a critical measurement since engine pressure data is corrected to standard day conditions based on barometric pressure.

During the engine development process, performance studies are made of each engine module to determine what happens to the air as it is compressed, turned, and expanded. As many as 100 to 200 sensors may be located at a single stage to determine pressure or temperature profiles. These are generally located in the leading edge of compressor or turbine vanes. Another common technique to obtain profile data is to traverse temperature and pressure probes across an engine section permitting a large number of data samples to be taken. Recording this data requires an automatic data acquisition system for both control and acquisition functions.

LINEAR AND ANGULAR POSITION MEASUREMENT

Linear potentiometers are used to measure linear or translational position. Even though the accuracy of linear potentiometers is quite satisfactory, they have certain disadvantages; the main ones being noise, sensitivity to vibration, and a relatively short life expectancy. Since the potentiometer is a contacting type device - a wiper making contact with a resistance element - it is best suited for applications where vibration levels are low. Where environmental conditions are not favorable, the linear variable differential transformer (LVDT) is preferable because there is no mechanical contact between the stationary and movable components. Coupling between primary and secondary elements is accomplished through transformer action. LVDT's can be used for applications such as afterburner nozzle area measurement. They have been used in the past in high temperature and vibration environments with little or no cooling, demonstrating high reliability and repeatability.

Rotary potentiometers are used to measure angular position such as power lever and vane angles. They have been used on almost all variable geometry engine development programs. Like its linear counterpart, the rotary potentiometer has mechanically con-

tacting elements making it sensitive to wear, resulting in non-linearities, inaccuracies, and frequent failures. In recent years resolvers have been evaluated and are now gradually replacing rotary potentiometers in measurement and control applications. Resolvers are non-contacting type devices, less sensitive to vibration and high temperatures, and have a much lower failure rate. Its specifications are at least as good or better then those of potentiometers.

When using a linear or rotary potentiometer a voltage is applied across a resistive element. The voltage at the wiper represents position and this signal is presented to a control room display or to a data acquisition system. Position sensors are generally calibrated by manually moving the item being measured from one known position to another or between physical stops where the dimension or angle is known. The uncertainty of this type of sensor is +/- 1% of full scale. Costs are $100-200.

ROTOR SPEED MEASUREMENT

The measurement of engine rotor speeds is made primarily with magnetic transducers similar to those used with flowmeters. The transducer is mounted in close proximity to a gear and the impulses generated by gear rotation are counted electrically in reference to a time base. An assembly, including a gear and several transducers, is mounted on the engine gearbox or in the inlet nose cone. In some applications, magnetic transducers are mounted on an engine inlet fan case to detect passing of rotor blades. In situations where blades are non-magnetic, such as titanium, an eddy current sensor may be used. Another technique is to measure the frequency of the engine alternator or generator output. In all cases an a.c. signal is generated that is proportional to engine rotor speed; however, a multiplying factor must be used to convert frequency to rotor speed. This factor depends on the location of the sensor used and must consider the gear ratio between engine rotor and sense point, the electrical characteristics of the alternator or generator, or the number of rotor blades at the transducer location.

The rotor speed sensor signal is connected to a digital preset counter in the control room for a test stand indication of speed. Best results are obtained by setting the counter on a 10 second counting period to provide a good average of rotor speed. Another piece of equipment is needed when rotor speed is recorded with a data system. A frequency to d.c. voltage converter is used to convert the frequency to a signal the data system can record. The system is very linear and calibrated by using a frequency generator to simulate the sensor output. Uncertainty of +/-0.2% of point can readily be achieved for speed measurements. Magnetic sensors are relatively inexpensive; approximately $200.

POWER EXTRACTION

Various aircraft or engine accessories are driven from power extracted from the engine. Compressor discharge bleed air may be used to drive air-conditioning units and hydraulic pumps and provide air for cabin pressurization and anti-icing at the engine inlet. Other accessories are driven by means of a direct, mechanical drive operated by gearing from the compressor-turbine drive shaft. The most common device for measuring mechanical power extraction is the hydraulic dynamometer, commonly called waterbrake. The power to be absorbed is transmitted to the waterbrake shaft which has vanes or perforated discs on the rotor. Similar vanes or discs are located on a fixed stator. The resistance offered by the coupling medium, water, to the motion of the rotor reacts upon the fixed stator which tends to rotate the case. This motion is counteracted by a load cell and lever arm configuration measuring the torque absorbed by the waterbrake. Horsepower extracted is calculated using shaft speed and measured torque. The torque measuring system includes a known lever arm and calibrated load cell. The load cell may also be calibrated in place by applying known weights to the lever arm to exert a force on the load cell. The alignment of the water brake and torque measurement system with the item under test is most critical. Measurement uncertainty is approximately +/- 1% of full range of the waterbrake and costs vary according to size; smaller units are $10-$15,000.

TRANSDUCERS AND SYSTEMS FOR ENGINE HEALTH MONITORING

VIBRATION MEASUREMENT

The primary concern of the test operator will be whether the vibration of the engine exceeds safe operating levels. Limits can be predetermined and, if exceeded, an alarm can be activated to alert operating personnel. Vibration can be expressed as displacement, velocity, or acceleration. While the electrical output of a transducer can be scaled in units of either by electrical integration or differentiation, the basic transducer actually responds to one of these three modes. Which transducer is best for a given application depends upon the frequency spectrum of interest and the permissible size and attachment.

The velocity transducer has a seismic mass constrained to linear motion along one axis, perpendicular to the transducer mounting base. The motion of the seismic mass relative to the mounting base gives relative motion between a coil and a magnet such that a voltage is generated proportional to the instantaneous velocity of the motion of the vibrating object. Some designs must be adjusted differently for horizontal than for vertical measurement, so velocity transducers should not be moved from one orientation into another without checking that feature. The working frequency range, depending on the design, can go from a low end of 5 Hz to a high end of about 1000 Hz. Velocity transducers have relatively low electrical impedance and enough electrical power in the signal so that simple signal leads to the amplifiers can be used without problems from stray noise.

Accelerometers have a seismic mass very rigidly mounted on a stiff spring made of piezoelectric material. The natural frequency may be 20,000 Hz or more. The force required to accelerate the mass is transmitted through the piezoelectric support, generating an electrical charge proportional to instantaneous acceleration. Accelerometers are usually used above 2 Hz to an upper frequency limit at least half of their natural frequency. Accelerometers have several advantages over velocity transducers. They are accurate to both lower and higher frequencies and are more reliable since they have no moving parts. They are available for use at temperatures up to 1200°F while velocity transducers are limited to 500°F applications. On light structures it is frequently impossible to attach velocity transducers without unacceptably changing the vibration as they are relatively large and heavy. Accelerometers are much smaller and can be mounted in many places impossible with the larger velocity transducer. The disadvantage of accelerometers is their very small output power. Special preamplifiers must be used with special low noise coaxial cable between accelerometer and the preamplifier.

All of the vibration sensing devices mentioned above put out electrical signals with an a.c. wave form which is the analog of vibratory motion. It is usually a complex wave with components at several frequencies simultaneously. There are various ways of converting this signal to useful information. If frequency content is not of interest a vibration meter can read either the peaks of the vibration or the rms value. An oscilloscope or oscillograph can be used for seeing the wave form so that a general impression of vibratory behavior can be observed. If frequency content is of interest, the vibration signal is connected to a frequency analyzer or recorded on a magnetic tape recorder for later off-line analysis to determine the amplitude vs frequency spectrum of the complex signal. The amplitude uncertainty of such a system is approximately +/- 6% of full scale. Vibration transducers are calibrated over their operating range on an electromagnetic shaker with a reference standard transducer. Accelerometers cost approximately $400.00.

Sophisticated computerized vibration alerting systems are available that can monitor several vibration transducers and engine speed on many engines, effectively in real time. The system will compare previously recorded vibration signatures (amplitude vs rotor speed) and alert the operator if any preprogrammed limits are exceeded. An automatic printout of parameters and cause of the alert is generated along with a spectrum plot of the out-of-limit parameter. Such units cost approximately $200,000.

ANNUNCIATOR SYSTEM

Many systems can be utilized to monitor engine health and provide for safe engine operating conditions. Most common is an annunciator panel which will display an out-of-limit condition of any of several critical engine parameters. Depending on limits set and alarmed, the test operator will return the test engine to idle speed or immediately terminate the test. Typical engine parameters monitored are; fuel inlet pressure to the main and afterburner controls, engine oil pressure, turbine temperature, vibration and engine rotor speeds. Sensors can be pressure switches or other transducers with comparative electronic circuits and relay closure contacts. In engine development facilities with large digital data acquisition systems 50 to 60 parameters can be monitored and out-of-limit conditions displayed in a timely manner to the test stand operators graphical display. Color graphical displays can provide a color change when an alarm condition is reached and a second color change when an abort condition is reached.

AUTOMATIC ABORT SYSTEM

During an engine development program, test conditions are more severe than in overhaul programs and any major damage to an experimental engine can have a significant impact on the development schedule and cost picture. An automatic test termination system may be used to help prevent major engine failures. When predefined engine operating limits are exceeded the system will detect overlimit conditions and shut the engine down. Critical engine parameters such as turbine inlet temperature and engine rotor speeds are monitored in the engine control room and presented to electronic circuitry where the desired shut down limit is set.

When any limit is exceeded a relay module is actuated which results in an automatic shutdown of the engine. System costs are approximately $25,000.

CONTINUOUS MONITORING SYSTEM

Another technique commonly used does not ensure engine health but is a useful tool in assisting test personnel to analyze engine conditions, after the fact, in the event of an engine malfunction. A continuous monitoring system is just that. Several key engine parameters; speed(s), fuel flow, burner pressure, turbine inlet temperature, power lever angle, exhaust nozzle position and vibration are recorded on magnetic tape. A relatively slow tape recording speed is used to achieve a long duration recording time or a continuous loop tape recorder may be used to obtain this same result. The tape recorder is automatically turned on and off by movement of the engine power lever in the control room. This system provides information on critical engine parameters in the event of an engine malfunction or failure. Data from tape is then played back and recorded on an oscillograph recorder for analysis. This system should be calibrated at a periodic interval primarily to be sure the system is operating correctly. The absolute accuracy of recorded parameters is not of prime importance since the purpose of this system is to obtain a time history of engine parameters immediately preceding an engine malfunction. Cost for this type of system including signal conditioning electronics, tape recorder, and oscillograph is $40,000 to $50,000.

MEASUREMENT UNCERTAINTY, ERRORS, AND CALIBRATION

It may seem obvious to say instrumentation must be accurate, yet uncertainty is inherent in the measurement process. Uncertainty is composed of two types of errors; first the degree to which measurements within a set will differ (called the precision error); and second the extent to which the average of that set will differ from the average of another similar set of measurements (called the bias error). The sets may consist of calibrations in laboratories versus those at a national standards laboratory, test of a single engine tested at two different test stands, winter tests vs summer tests, tests before and after a change in engine configuration, or any other comparison that may be of interest. The terminology and methods for treating uncertainties are well covered in the handbook "Uncertainty in Gas Turbine Measurements" by Dr. R. B. Abernethy and will not be detailed here. The main point is that for successful testing the precision errors must be minimized by good instrument design so that the bias across a small change in engine configuration can be identified with statistical significance.

Any deviation between a measured value and the true value for a particular parameter is considered as an error. Errors may be known and corrections applied to the measured data to eliminate the error. For example corrections can be applied to fuel flow measurement data as a result of specific gravity change of fuel as a function of temperature difference of the fuel between laboratory calibration and test conditions. Errors may be known to exist but cannot be quantified. For example engine inlet pressure, PT2, is used in the calculation of engine pressure ratio. However, measured PT2 may be the pneumatic average of 5 to 7 individual probes while the true PT2 will depend on inlet pressure profile.

The common sources of error which cause the data to scatter can be grouped in three catagories: variability in the engines themselves, variabililty in test conditions, and measurement uncertainty. The engine variabilities contributing to data scatter include manufacturing tolerances on parts, changes in vendors, and uncontrolled variations due to difference in assembly techniques and skill. Engines do not repeat perfectly even when rebuilt with the same parts after a teardown. Common variabilities in test conditions include different stands, operation in different weather conditions, or using different fuels, and using different personnel or operating procedures. Weather conditions produce complex data scatter on outdoor stands where wind direction, velocity, and turbulance add to effects of ambient temperature and humidity. Weather conditions also affect indoor stands in producing pressure and temperature inlet distortions, re-ingestion of exhaust from nearby stands and, in winter, severe temperature gradients when an engine at room temperature starts up, heating large volumes of air from near zero to several hundred degrees in a few minutes. Fuel from different suppliers may vary in density, affecting the calculation of thrust specific fuel consumption. As fuel flows from outdoor plumbing through the flowmeter and pumps to the engine its temperature and hence density will change rapidly. Because many of the above are highly seasonal it is obvious that back to back tests extending over a few months, which is not unusual, may need lots of care. Changes in stand personnel is most important in the degree of adherence to the the same operating procedures including instrument calibrations, acceleration rates, stabilization times, etc. The precision of the test results can be no better then the precision of duplicating the test conditions. Uncertainty in the measurements themselves are primarily caused by instrument characteristics which change with time or with some environmental parameter. Instruments should be calibrated periodically to reveal aging characteristics. Special studies should be conducted to assess the temperature characteristics of sensors or the effect of viscosity on fuel flowmeters, etc. The errors discussed above may be bias errors.

Further, precision errors can be caused by abnormal friction in thrust suspensions or turbine meter bearings, fluctuating temperatures at thermocouple reference junctions or at transducers, etc.

A measurement system is composed of many subsystems each interfacing with the next. The performance charactersitics of each subsystem from the transducer, instrumentation cables, recording equipment, and including processing equipment must be understood in order to obtain valid data. Individual electronic instruments and transducers are usually calibrated in a laboratory using detailed procedures and equipment under known and repeatable environmental conditions. It should be realized that calibration data, determined in the laboratory, may not be directly applicable at the test stand. Ideally one would like to duplicate the actual test conditions during the calibration process but this is seldom possible within the scope of engine testing. For example summer or winter testing conditions may be significantly different from laboratory conditions. Detailed calibration techniques for various transducers and measurement systems required for sea level engine testing are beyond the scope of this paper. However, one point is worth repeating; the calibration process and measurement process are two separate functions unless the environment of the total calibration process exactly duplicates the environment of the measurement process. Any deviations must be considered in the calculation of measurement uncertainty.

Most contracts require a test facility to trace the accuracy of measurements to a common accepted reference such as the National Bureau of Standards. The standard practice is to calibrate the working instrument against a hierarchy of reference instruments ending with a primary national standards laboratory calibration. Having the capability for traceability of data through a calibration system does not improve the uncertainty of the measurement process. This capability only defines the uncertainty of the calibration system and establishes the physical capability to determine a bias in a measurement system. Really, traceability is nothing more then documentation of what procedure was used, what instruments were used, and when and how they were calibrated.

DATA ACQUISITION

Some engine test stands utilize analog or digital displays in control rooms for obtaining information. Data from 30-40 parameters are manually recorded during engine steady-state conditions, and calculations to determine engine performance are made manually or by use of small desk top computers. In engine development programs it is not unusual to record 600 or more parameters during an engine test. This volume of data requires an automatic data acquisition and processing capability. The general objectives of modern computer based performance data acquisition and processing systems are to acquire temperature, pressure, position, frequency, etc. data, convert it to engineering units, make quick look performance calculations, and present output data and results. The recorded and calculated parameter data are available for display in graphical or alphanumeric form to the test stand operator within 1-2 minutes and detailed off-line calculations of data are available for analysis by performance personnel within a few hours. Capabilities vary among systems, but all include the ability to accept transducer calibration data and computing capacity to apply it as directed. The nominal uncertainty for this type of system is +/- 0.1% of full scale. System costs depend upon number of channels, computer size, recording speed, etc., are $25,000 to $100,000.

Recording data during transient engine conditions is much different than steady state conditions. Various systems are available and each has advantages. Simple strip charts or X-Y plotters are inexpensive ($1,200) but are limited to one or two low response (10 Hz) data channels. A typical application of an X-Y plotter is to record the ratio of fuel flow to burner pressure on one axis and engine speed on the other axis. Approximate measurement uncertainty for these units are +/- 2.0% full scale. The recording oscillograph also presents a time history of dynamic events with a capability of recording 20 to 30 parameters at frequencies to 5000 Hz. The concept requires a transducer, signal conditioning amplifier and galvanometer which deflects a beam of light, proportional to the physical occurrence, on light sensitive recording paper. Data uncertainty for this type of instrument is +/- 5% full scale and cost of a 12 channel unit is $6,500.

The most common device used for recording dynamic data is a magnetic tape recorder. Using frequency modulation techniques, data may be recorded over a frequency range of 0 to 20,000 Hz. Amplitude modulation techniques extend the high frequency capabilitly to at least 100,000 Hz but the low frequency end is degraded. Frequency modulation tape recording techniques are commonly used in development programs during stress investigations of rotating hardware, vibration surveys of engine components and dynamic pressure surveys at the engine inlet. Data are usually processed in off-line facilities. Data uncertainty is +/- 5% full scale and cost of a 14 channel tape recorder is $50,000.

Digital recording systems can also be used for recording dynamic events. However, data sampling rate and computer size must be significantly increased which will result in a 10 times increase in system costs. Digital systems have the advantage of better uncertainty, higher quality data, and faster operating modes than analog systems. Analog systems have a lower initial cost but are labor intensive to operate and require manual data reduction to analyze the engine event.

Calibration of data systems are periodically performed by substituting transducer signals with known amplitude levels or frequencies traceable to a national standard and operating the system in its normal mode.

CONCLUDING REMARKS

This paper provides general information in the application of instrumentation devices and measurement systems used during turbojet and turbofan engine testing. It is for the use of test facility operators or other personnel recently exposed to measurement problems. The final section of this paper provides a bibliography of useful references for further study by those in need of a more in-depth understanding of instrumentation or measurement engineering practices.

FOR FURTHER READING

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PERFORMANCE DERIVATION OF TURBOJETS AND TURBOFANS FROM TESTS IN SEA-LEVEL TEST CELLS

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SUMMARY

To most users of aircraft jet engines, the definition of engine performance means the thrust level, and the fuel consumption required to generate it. Just as important, however, is mechanical performance, as an engine may meet the thrust requirement, yet lack sufficient mechanical integrity. The operator must therefore have some means of quantifying engine performance before he can pronounce it as healthy. This type of routine testing is generally conducted in an enclosed ground-level test bed.

During an engine test, data are recorded at several power settings, corrected for cell effects, and compared against manufacturer's supplied curves to determine actual performance. If an engine was tested on an outdoor stand, under zero wind conditions, the measured thrust, corrected for instrument error, would be the true engine thrust. The act of bringing the engine into an enclosed facility has an effect on measured engine performance. The procedure for quantifying this effect, sometimes called establishing a cell-factor, is usually done by correlating the customer's facility to the manufacturer's standard test cell using a "gold-plated" engine.

This paper describes the types of measurements, performance parameters, and methods of data presentation for a correlation program.

1.0 INTRODUCTION

Since the introduction of gas turbines for aeropropulsion, engine designers have had to make predictions as to the expected performance. Design procedures were established wherein component characteristics were estimated, then the components matched to each other, and finally analytically assembled to define a complete powerplant. Depending on the quality of component data, installation effects, and assumptions of parasitic losses, the built-up unit could pass or fail the performance targets. Complete powerplant, rather than component testing was, and still is, the only way to demonstrate to both the manufacturer and the client that his product can meet specified performance objectives.

Engine testing, be it for shaft power or turbojet/turbofan units, brings along with it a great number of uncertainties. The geometry of the test cell, engine environment, quality of instrumentation, number of sensors, data acquisition, and data reduction techniques significantly affect the quality and accuracy of test data. Of particular importance are the corrections that have to be applied to the measurements to reduce or eliminate instrumentation biases. Derived data also have to be corrected for temperature, pressure, and humidity to reduce the results to a standard reference condition. Furthermore, the enclosure itself, especially if it is of small cross-section can have a considerable influence on engine performance, particularly on thrust accounting. Keeping in mind that many engines have only a small performance margin over the guaranteed value - typically 2-3% - the test facility must then be capable of consistently resolving performance down to very small levels. For an engine manufacturer or a research facility, the accuracy may be in the order of 1% or less, whereas for a military test stand an accuracy level of 3-4% might be acceptable.

One area of great concern to engine test facilities are the techniques used to compare engine performance amongst them, knowing that cell type and instrument quality play a significant role in performance measurement. An engine manufacturer will state that an engine produces a specified level of performance in his test cell using his own cell correction factors. If a user then wishes to relate engine data from his test cell to the manufacturer's, he must participate in a correlation program involving a designated engine of known performance, which is tested in both facilities. The result of the test program would be the determination of corrections to the reduced data. For example, one of the corrections is called a cell factor, which correlates the thrust measurement in both facilities.

This paper outlines the purpose of engine testing, as each user has his own specific end-use requirements. The various types of test facilities are then briefly described including outdoor and enclosed ground level test beds for installed (on-wing) or uninstalled testing, and the altitude test bed. A section is devoted to instrumentation, and specifically to the difference between correlation and general instrumentation. Next is a treatment of cell effects - what are they, what causes them, how to minimize them, and how they impact the data. This is followed by a discussion on

measured and derived engine parameters, and the types of correction factors needed to reduce the data to a common base.

The last section deals with data analysis and presentation. It begins with an elementary treatment of measurement uncertainty to remind the reader that all test data contain errors. This knowledge is especially important when data are being compared between facilities, as the results are data bands rather than discreet points. Several approaches to present results are described, with a discussion on the merits of each.

2.0 PURPOSE OF ENGINE TESTING

The various types of propulsion testing can generally be divided into four basic categories: design testing, proof testing, capability testing, and trouble-shooting.

Design testing, normally carried out by the engine manufacturer, centers on major components or small bench set-ups. The results from these tests are used to validate or to correct computed designs, and to optimize such elements as cooling passages, blade angles, boundary layer correction factors, and temperature profiles. A typical approach is to design the parts based on experience and theory and then to check the components or elements on bench tests. At this time variable geometry schedules can be optimized, three-dimensional effects examined, and minimum tip clearances adjusted.

Proof testing is done by the manufacturer to show that his powerplant meets design specifications. The specifications may call for a large number of tests in addition to a long and complex endurance test that may involve many throttle movements, altitude testing, and running on several fuel types. Only when all these tests have been successfully completed can the engine be properly considered certified.

Capability testing may be undertaken by the manufacturer or carried out in concert with the client if he is a large operator like the military. Such efforts might test the effect of errors in adjusting the engine, lapse rate of performance with usage, manoeuvre limitations caused by inlet distortion, limits on afterburner light with respect to altitude and speed, engine relight limits, surge and stall limitations, low cycle fatigue life, flutter boundaries, and stress rupture life.

Trouble-shooting is a testing function necessary to solve problems that occur in the field after a period of use. In some cases it is necessary to duplicate not only the failure mode, but the elapsed number of cycles or time in the engine life when the failures occurred. Many engine types were originally conceived for an application which may be quite different from current use, thus imposing new constraints that were not originally provided to the design engineer.

The above four categories of testing, may be generally classified as supporting research and development (R&D). Although more routine, production testing and post-overhaul acceptance testing are nonetheless important. The class of facility required for research and development testing is generally quite complex and expensive, as simulation of both altitude and forward speed, in addition to sea-level static conditions, may be required. Production testing, carried out under sea-level static conditions by the engine assembler, is required of each engine to ensure that it meets performance guarantees. Due to tolerances in the production of individual parts and in the build-up of the assembled components, each engine will have a unique performance signature. The production test, using minimal instrumentation, logs engine performance and health, adding new information to the manufacturer's data bank. This test also demonstrates to the client that each unit meets specification.

Post overhaul acceptance testing has the same objectives as production testing in that the engine must meet minimum performance targets. While production engines contain all new parts, overhauled engines may contain some repaired parts with the bulk of the parts being "used". Repair methods and deterioration limits are initially set by the engine designer, but it is only through the feedback of field and overhaul data that the effectiveness of parts recovery schemes can be quantified. The overhaul facility, which may be owned by the user, ie: an airline or the military, has a dual role to play; it must satisfy the user who wants engine integrity and performance restored at minimum cost, and it must also cooperate with the engine manufacturer who is the design authority and also a vendor for new parts. Thus, the post-overhaul acceptance tests are quite important, as the engine will seldom exhibit "as-new" performance, yet it must pass minimum performance guarantees.

Finally comes the end user. Engine service technicians must respond to pilot complaints about inadequate or erratic engine performance, be it real or imaginary. Sometimes the problem can be rectified "on-wing" without engine removal, but often, especially with older designs, the engine must be installed on a test bed to isolate and repair the fault. Current design practise does permits a number of components, such as electronic fuel controls, to be changed on-wing, provided the fault can be isolated. Fault isolation may be effected by test equipment that does not require engine operation, but if required, the test facility must be capable of monitoring engine performance while installed in an aircraft. Based on the results, the technicians may remove the engine, replace components or engine modules as necessary, then re-test before reinstallation.

The objectives of the engine service technician are somewhat different from the engine overhauler. Ideally, he would like a green or red light to indicate whether an engine passed or failed a test. Typically, he is looking for oil and fuel leaks, speed or temperature exceedances, and any mechanical problems while checking geometry schedules and transient performance. Satisfied, he may then consider the level of fuel flow and thrust. Remembering that his primary function is to keep the airplanes in the air, he does not place the same degree of importance on the accuracy of 'performance' parameters like fuel flow and thrust measurement as does an R&D organization or engine manufacturer. However, with the advent of "on-condition" maintenance at the operational level, albeit not thus far very successful, more attention has to be paid to thrust and fuel flow, as they are known to be key parameters in assessing engine health along the gas path. Previously he could rely on the overhaul facility to restore engine performance, but now the responsibility is being shifted towards the individual base to identify low performance engine modules. Hence, the field test facility now requires a better standard of instrumentation, data gathering and handling, and engine performance assessment.

3.0 ENGINE TEST FACILITIES

Engine test facilities are designed to evaluate engine operational and performance under well controlled conditions. They are divided into two basic classes, the Sea-Level Test Facility (SLTF) and the Altitude Test Facility (ATF). The most common is the SLTF in which the engine operates under the prevailing environmental conditions. Altitude Test Facilities are provided with extensive compressor, exhauster, heater and dryer equipment in order to independently control air temperature and pressure at the engine inlet, and ambient pressure surrounding the exhaust nozzle(s). These capabilities permit the engine to be operated in conditions simulating a wide range of pressure altitude and aircraft flight Mach numbers.

3.1 Sea-level Test Facilities

Sea-level test cells are more prevalent than altitude cells primarily due to the on complexity and capital and operating costs. Despite the limitation of the sea-level or ground level test bed, it still serves as a cost effective tool at the production, post-overhaul, and R&D level.

Sea-level cells can be sub-divided into two groups, the outdoor stand, and the indoor or enclosed test cell. Of the two, the outdoor stand is less common, although it provides the best possible datum to which the 'artificial' situation of enclosed test cells, both sea-level and altitude, can be compared. Its major limitation is that it is subject to the ambient environment, data quality being strongly affected by wind strength and direction, humidity, and precipitation. Before discussing the merits and drawbacks of the various facilities, a brief overview of test objectives and performance measurement is required. A more detailed treatment will be presented in a later section.

Engine performance is generally defined in terms of engine airflow, fuel flow, and thrust. Thrust is usually measured by mounting the engine in a framework which, itself, is suspended from a fixed structure by means of flexures. This arrangement enables the engine in its framework to move freely only in the axial direction. The amount of axial movement is restrained and the resulting force measured, normally by a strain gauge load cell. The air intake to the engine is generally a bellmouth or a venturi designed as an air meter. This inlet is normally mounted on the thrust bed, so that under static conditions the force on the framework, measured by the load cell, is very close to the gross thrust of the engine (Figure 1, obtained from Ref. 1). Not shown is a debris protection screen in front of the air intake that is often directly attached to the bellmouth. Screen losses must be quantified and adjustments made to the measured force to obtain gross thrust.

Airflow is calculated from pressure, temperature and area measurements at the throat of the air meter. The air meter itself has to be calibrated against another standard, or by carefully traversing the throat with pitot probes and establishing a flow coefficient. The accuracy and repeatability of this device may be affected by flow distortion or turbulence approaching the engine.

Figure 1a schematically represents an open air test bed. The thrust stand is located at a suitable elevation off the ground to eliminate inlet flow interference. If the testing is conducted in the absence of wind, there will be no approach momentum, nor static pressure gradients along the engine. Measured scale force will then be the gross thrust. As such conditions are rare, testing with a wind blowing requires alignment of the inlet with the wind direction. If the head wind is not greater than 5 m/s, the resulting free stream momentum correction to measured thrust will then be in the order of 1%.

Enclosure of test cells requires further thrust corrections. The most usual form of SLTF (Figure 1b) has an ejector tube or detuner that collects and silences the exhaust and provides cell scavenging. Entrained secondary air is drawn over the engine from the test bed intake. Engine air is directed to the inlet venturi with a measurable velocity, which leads to an approach momentum force deficit on the bellmouth. This increased approach momentum has to be properly credited to the engine as it is the prime mover responsible for accelerating the air from rest to the prevailing cell

velocity. Drag forces are exerted on the engine external carcass and thrust stand, and the static pressure around the engine is modified to a small degree. Further corrections thus have to made to the measured load cell force in order to obtain gross thrust.

The load cell measuring system must also be calibrated. The calibration is done in-situ by applying axial loads to the complete engine/frame assembly at the engine centreline via a master load cell system. Since the flexures behave like springs and the engine mass may distort the frame, the actual engine or its equivalent mass must be installed on the bed for the centre-pull calibration.

The corrections to the measured load to obtain gross thrust are derived by one of two ways, a) by a careful cross calibration with an open air test facility or another reference facility of known performance, or b) by computation using air velocities and pressures measured in the test cell. It should be noted that these corrections are particular to the engine type and test cell arrangement. The magnitude of the corrections are a function of engine power setting and can vary from zero up to 8%.

A variant of the SLTB is the Hush House which can test the engines installed in the airframe (Figure 1c) as well as uninstalled. Particularly troublesome is the case of twin-engine fighter planes as the exhaust collector must now be sized to simultaneously collect the efflux from both engines, yet is oversized for testing a single unit. Another complication arises with vertical or side entry air inlets, which in combination with the oversized collector, can lead to unstable and multidirectional secondary cooling airflow. In this instance, analytical procedures for arriving at cell correction factors are virtually impossible, and requires a cross calibration with a facility of known performance.

3.2 Altitude Test Facilities

An essential feature of Altitude Test Facilities (Figure 1d) is the separation of the inlet of the engine from the exhaust which permits the engine operating envelope to be explored over a wide range of altitude and Mach numbers. Additional investigations are thus possible such as thrust lapse rate with inlet temperature or pressure, sensitivity to inlet distortion, engine afterburner light limits with altitude and speed, engine relight, and blade flutter boundaries. This capability comes at quite a considerable cost as extensive plant equipment is needed, access to a large power source, and a substantial support staff to operate and maintain the facility.

Thrust measurement and accounting procedures are different than in sea-level facilities. A slip joint physically separates the inlet section from the engine providing a plane at which all the inlet forces can be accounted. Scale force measured by the load cell no longer represents gross thrust, but the difference between forces at the slip joint and the exhaust nozzle. Allowances have to be made for external pressure forces along the engine carcass, skin friction drag resulting from chamber cooling flows, stand drag, and other parasitic forces.

4.0 TEST CELL INSTRUMENTATION

Instrumentation in test cells is often categorized into two groups, one for general engine operation and the other for evaluating engine performance. Operational instruments are those used to measure rotor speed, exhaust gas temperature, vibration, oil pressure and temperature,fuel pressure, and perhaps power lever angle. Performance instrumentation are those systems that are needed to calculate fuel flow, gross thrust, and airflow. All facilities routinely measure fuel flow as it is an easy parameter to measure, however determining gross thrust is more involved. A net scale force from a load cell may be recorded, but the cell effects have to be quantified and added to the scale force to yield gross thrust. Some manufacturers correlate test cells on the basis of engine pressure ratio which can be related to gross thrust. This relationship is valid for a fixed nozzle engine and is even used on variable nozzle engines, provided the variable geometry settings are measured. Careful measurement of cell and engine airflow are particularly important for turbofan engines as a large portion of their thrust, depending on bypass ratio, is derived from the fan stream.

4.1 Airflow Measurement

Direct measurement of engine airflow is, in most cases, obtained by the use of smooth-approach orifices conforming to ASME standards. These air meters are either attached directly to the engine inlet duct or built into the engine inlet room supply system. Figures 2 and 3 show both types, the former used in sea-level cells directly coupled to the engine, and the latter used in altitude cells decoupled from the engine by a free-floating labyrinth seal. Airflow is deduced by measuring the velocity profile with pitot-static probes at a high velocity plane of known geometric area. By integrating the elemental mass flow at each probe using the inlet temperature and physical properties of air, total airflow can be calculated. A Reynolds number sensitive flow coefficient obtained by either calibrating against a reference meter or boundary layer measurements, modifies this value to yield an actual airflow.

This rigorous and high accuracy procedure for airflow measurement is necessary for a cell correlation program, but at a production or field level, the inlet rakes are considered a high maintenance item and are not generally installed. Several simplifi-

cations of the rigorous method are possible while still yielding reasonable airflow measurements. Air temperature is measured by an array of thermocouples attached to the inlet screen. Total pressure in the bellmouth is related to a test cell ambient pressure located at a forward location on the test cell wall, and the throat static pressure probes are replaced by bellmouth wall statics. A single flow coefficient, rather than one that varies with Reynolds number, then enables airflow to be calculated If the location of the engine is changed or the inlet geometry of the cell is altered, a recalibration of the bellmouth using a full complement of rakes may be necessary.

4.2 Fuel Flow Measurement

The most commonly used system to measure fuel flow is a volumetric turbine type device coupled to a variable time base digital readout instrument. The sensors, at least two in series, when installed with flow straighteners upstream and downstream, are accurate and reliable. Fuel density and viscosity are calculated from temperatures measured at the meters. If a wide range of flow is required, as in the case of after-burning engines, a multi-manifold fuel system should be installed near the fuel inlet to the engine. With time, bearing wear will degrade the accuracy of the meters and introduce non-linearities in the low flow range. For this reason, periodic calibrations are necessary. A typical calibration is shown in Figure 4. The required inputs are frequency and viscosity (temperature dependent); with the output the so called "K" factor. Actual fuel specific gravity at the fuel temperature and the frequency are combined to produce actual gravimetric fuel flow.

4.3 Scale Force Measurement

The system most commonly used to measure the thrust of a turbojet/turbofan utilizes strain gauge type load cells. They may be mounted near the front or at the rear of the thrust stand in compression or tension. The forward location is preferred to reduce the possibility of errors due to thermal radiation from the engine exhaust. The thrust measuring system should be designed to minimize false loading of the load cell due to temperature gradients in the structure and/or calibration in a different horizontal plane than the thrust loading.

The three basic flexure designs most commonly used with thrust stands are compression, tension, and compound. Flat plate flexures should only be used in tension, whereas compound flexures have been satisfactorily employed in both tension and compression. A schematic of an engine installation on a floor mounted stand with flat plate flexures is shown in Figure 5. A centre-pull calibration with the engine in place is mandatory, as the pitching moments induced in the stand can cause the flexures to change loading from tension to compression. Should this happen, the calibration will likely be non-linear, unrepeatable, and sensitive to changes in mass.

Stand stiffness, spring rate, and hysteresis have to be accounted for as there may be measurable deflections of the thrust bed relative to the ground reference. Squeezing the thrust bed with a reference load cell in the plane of the measurement cell could conceivably calibrate the overall system on a routine basis. However, because the engine thrust vector is some distance above the load cell, a regular centreline thrust calibration is the true procedure needed to compensate for any moment effects (Figure 6).

4.4 Engine Inlet and Exhaust Conditions

Since engine performance is quite sensitive to inlet temperature, it is extremely important to accurately measure that temperature. An average inlet air temperature, can be obtained by locating a sufficient number of sensors ahead of the engine inlet. If cell cooling air is inadequate, or under peculiar wind conditions, exhaust gas may be reingested into the inlet and influence engine performance. Engine location in the cell and the ratio of engine nozzle to collector diameter control the amount of cooling air being pumped through the cell. The inlet temperature probes would be the primary aid for diagnosing exhaust gas reingestion. Once a suitable configuration has been selected, the number of temperature sensors at the inlet could be reduced.

Engine inlet pressure is defined as the average pressure in a plane normal to the engine centreline several centimeters forward of the bullet nose. This pressure is calculated from upstream pressure measurements in the bellmouth (in outdoor free field testing this is the local atmospheric pressure) with an allowance for drag caused by the rakes and duct wall friction loss. If an inlet screen is used (to prevent foreign object ingestion during testing), a measurable pressure loss may occur. Accordingly, it will be necessary to either measure the inlet total pressure at the engine face in each test or to predetermine the screen loss and account for it in the data reduction process.

Test cell ambient pressure is usually considered to be control room barometric pressure in the control room adjusted for cell depression. It may be used for inlet total pressure if the air velocity in the cell is low, and an allowance is made for screen loss. High cell velocities, in excess of 8 m/s, will require a calibration between inlet total pressure and a cell wall static pressure located upstream of the bellmouth.

Engine exhaust static pressure is the static ambient pressure that the exhaust nozzle "sees" and is equivalent to in-flight ambient static pressure. It is measured by averaging several equally spaced static pressure taps at the base of the exhaust nozzle. Static ambient pressure is strongly affected by the cell geometry, nozzle to collector spacing, and the collector diameter. As this pressure is usually only directly measured during a correlation program, any correction factors arrived at could be invalidated if any of the above parameters are changed.

4.5 Engine Cycle Measurements

A correlation engine should be selected from those which have satisfactorily completed acceptance. It is desirable to obtain an engine with several hours of run time to reduce the possibility of early deterioration. Instrumentation should be installed that can detect small shifts in the thermodynamic cycle of the engine. For a turbofan engine, in addition to the previously mentioned parameters, the following measurements are required:

1) Fan discharge pressure and temperature
2) Compressor discharge pressure and temperature
3) Compressor discharge static pressure
4) Turbine discharge pressure and temperature
5) Fan and compressor variable geometry position
6) Exhaust nozzle area or position
7) Exhaust stack temperature
8) Cell cooling air velocity
9) Humidity
10) Fuel lower heating value

Careful monitoring of these parameters after correction for non-standard conditions can indicate the state of engine health.

5.0 CELL EFFECTS

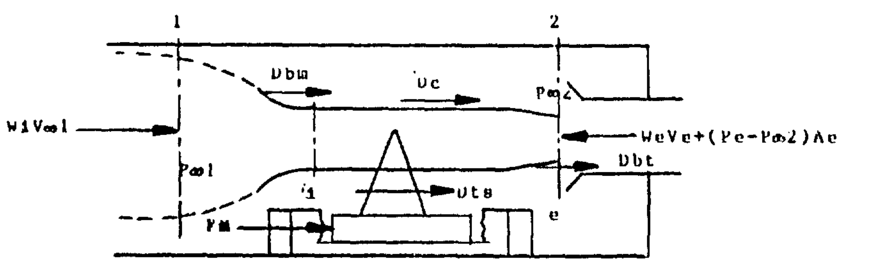
In the previous discussion on test cell types, the outdoor stand was held out as the standard against which indoor cells were compared. The act of enclosing the engine and directing the airflow through the cell brings with it a number of problems primarily related to the determination of gross thrust.

Test cell influence factors are dependent upon the configuration of the cell, the airflow demand of the engine, type of sound suppressor, and positioning of the engine in the cell. A cell with a horizontal air inlet reduces the likelihood of inlet flow distortion at the engine inlet. Pressure distortion at the bellmouth entry reduces the accuracy of the air meter and makes the definition of inlet pressure more difficult. Fan and/or compressor efficiency could shift, and the engine speeds may rematch on a multi-spool engine. For various reasons, some cells are constructed with a vertical or side inlets. In these cases pressure surveys near the bellmouth are required to assess flow quality before permanently fixing the engine location.

The exhaust collector diameter and its position relative to the engine nozzle affects the local static pressure at the plane of the nozzle and the total amount of secondary airflow through the cell (Ref. 2). The collector entrance is normally sized for minimum airflow consistent with the engine/cell cooling requirements, allowable cell depression, and minimum cell velocity. The total avoidance of static pressure depression at the engine nozzle requires ample spacing between the nozzle and the collector inlet. Increasing the spacing requires a progressively larger collector to capture the efflux, but secondary airflow increases rapidly as collector area increases. Therefore, location of the engine relative to the exhaust tube is a compromise to obtain proper operation with minimal corrections.

Air cooled cells designed for afterburning engines require larger corrections because of increased collector size. Some facilities water cool the collector when operating in afterburning, thus keeping its area consistent with dry operation.

Cell velocity must be accounted for in the engine performance. In qualitative terms, the engine is the prime mover responsible for accelerating the air from rest to the prevailing cell velocity, and this ram drag must be properly credited to the engine as a thrust correction to static conditions.



To better understand all the forces that need to be handled in an enclosed sea-level cell, a momentum balance can be drawn around the engine as shown on the previous page. In this case an inlet screen is not shown, but if it is attached to the bell-mouth, the thrust forces are accounted for.

Summing up the forces between plane 1 and 2

$$Fm + WiV_{\infty 1} + Dbm + Dc + Dts + Dbt = WeVe + (Pe - P_{\infty 2})Ae$$

where the terms above and to follow are defined as

- Fm = measured thrust from load cell
- Fn = net thrust
- Fg = gross thrust
- Fram = ram drag
- Wi = engine inlet mass flow
- We = mass efflux from the engine
- $V_{\infty 1}$ = free stream velocity upstream of engine inlet
- Ve = nozzle exit velocity
- Vo = equivalent flight velocity
- $P_{\infty 1}$ = cell forward static pressure
- $P_{\infty 2}$ = nozzle base static pressure = Pamb
- Pe = nozzle exit static pressure
- Ae = nozzle exit area
- Dbm = form drag of bellmouth intake
- Dc = skin friction drag on engine carcass
- Dts = form drag on thrust stand
- Dbt = buoyancy (boat-tail) drag on exhaust nozzle.

Considering that

$$(Pe-P_{\infty 2})Ae + WeVe = (Pe-P_{\infty 1})Ae + (P_{\infty 1}-P_{\infty 2})Ae + WeVe$$

and

$$Fg = (Pe-P_{\infty}2)Ae + WeVe - (P_{\infty 1}-P_{\infty 2})Ae$$

then gross thrust

$$Fg = Fm + WiV_{\infty 1} - (P_{\infty 1}-P_{\infty 2})Ae + Dbm + Dc + Dts + Dbt$$

and net thrust,

$$Fn = Fg - Fram$$

where Fram = WiVo.

Vo is the equivalent flight velocity based on the difference between inlet total pressure, P_2, (or $P_{\infty 1}$, if no significant losses occur due to screens at the engine inlet) and the base nozzle pressure, $P_{\infty 2}$. In effect, the engine appears to experience a forward flight velocity (Ref. 3).

A detailed treatment of the individual terms follows:

1) Inlet Momentum, $WiV_{\infty 1}$

Inlet velocity, $V_{\infty 1}$ can be calculated from total cell airflow at a particular accounting plane, $_{\infty 1}$. The common method employs an energy balance across the cell, provided exhaust stack temperature is measured.

$$W\ cell = \frac{1000 \cdot Wfe\ (LHV \cdot \eta\ comb + H\ fuel - H\ stack)}{H\ stack - H\ inlet}$$

and

$$V_{\infty 1} = \frac{W\ cell}{\rho_{\infty 1} \cdot A\ cell}$$

where

- W cell = cell mass airflow
- Wfe = engine mass fuel flow
- LHV = fuel lower heating value
- η comb = combustion efficiency
- H fuel = fuel enthalpy
- H stack = exhaust stack enthalpy
- H inlet = inlet air enthalpy
- $\rho_{\infty 1}$ = air density at plane $_{\infty 1}$
- A cell = cell cross-sectional area

If an engine is operated with afterburner and water cooling of the exhaust stack is used, this calculation procedure will not work. A wall static pressure could be calibrated against total airflow in the "dry" regime and airflow inferred from it when water cooling is used. Alternatively, approach velocity could be directly measured with anemometers. If cell velocity is kept below 8 m/s, an engine of the 70 kg/s airflow class would require a correction in the order of 1%.

2) Tailpipe Pressure Correction, $(P_{\infty 1} - P_{\infty 2})Ae$

With the engine tailpipe in close proximity to the exhaust collector, the secondary air must accelerate to pass through the annular gap. This accelerated flow causes the static pressure at the nozzle exit, $P_{\infty 2}$, to be depressed relative to the free stream static, $P_{\infty 1}$. The nozzle then exhausts into a lower pressure area and generates more thrust. Therefore, to correct back to inlet conditions, the area x pressure difference term must be substracted from the gross thrust. Typical values for a well tuned system are in the order of 0.3% gross thrust.

3) Bellmouth Form Drag, Dbm

The thrust contribution of the bellmouth, which is usually attached to the thrust stand, is directly credited to the engine and included as part of the scale force. High secondary airflow could give rise to horizontal pressure gradients along the engine, and in particular behind the bellmouth. If the pressure behind the bellmouth (Pb) differs from $P_{\infty 1}$, then an additional correction term $(P_{\infty 1} - Pb)$ must be applied over the projected annular area of the bellmouth. By keeping the secondary airflow low, Pb will be the same as $P_{\infty 1}$, thus requiring no correction.

In this treatment of the buoyancy terms in the test cell, the bellmouth drag, Dbm, and the boat-tail drag, Dbt, are treated separately. Normally a surface integral with respect to pressure along the exterior surface, omitting the inlet and exhaust planes, would encompass all the terms, but as $P_{\infty 1}$, is virtually constant along the skin except in the vicinity of the nozzle, these two particular areas are given special attention. If a test cell baffle wall is included at any point along the length of the engine, it may induce an appreciable pressure-area force which must be considered.

4) Skin Friction Drag, Dc

Scrubbing of the engine carcass by the induced secondary airflow results in a skin friction drag that must be credited to the engine. However, the values are usually negligible and can therefore be ignored.

5) Thrust Stand Form Drag, Dts

Secondary airflow also impinges on the frontal area of the thrust stand and creates an additional drag. An estimate of the magnitude can be made by using a flat plate approximation for a drag coefficient. Even though the computed values are small, they are normally included in the thrust accounting.

6) Buoyancy (Boat-tail) Drag on the Exhaust Nozzle, Dbt

Due to the close proximity of the nozzle exit to the collector inlet, the secondary airflow accelerates past the exhaust nozzle into the mixing tube, and sets up a static pressure gradient along the external surface of the nozzle. The generated net force can be calculated by integrating the surface pressures along the nozzle and resolving the horizontal component. By carefully selecting the insert size and proper spacing of the exhaust nozzle to the collector, this correction can be kept quite small.

6.0 PERFORMANCE CORRECTION FACTORS

All gas turbine engines are affected by the ambient conditions in which they operate. Measurements of airflow, fuel flow, and thrust are valid only for the test conditions of altitude, inlet pressure, ambient temperature, fuel lower heating value, and control settings. These values must be adjusted to a set of standard or specification reference conditions so that the thrust produced and fuel consumed can be compared with specification requirements. Since the method or values for correcting the performance parameters to a standard day condition often vary between different engine types and models, the procedures to correct these parameters are contained in that particular engine type model specification.

Early studies, employing dimensional analysis, revealed that the primary operating variables of a gas turbine can be normalized as functions of total temperature and pressure levels measured at the engine inlet, station 1. The basic normalizing parameters are:

$$\theta_1 = \frac{\text{observed inlet total temperature}}{\text{reference standard day temperature}} = \frac{T_1}{288.16\ K}$$

$$\delta_1 = \frac{\text{observed inlet total pressure}}{\text{reference standard day pressure}} = \frac{P_1}{1013.25\ kPa}$$

The major engine parameters are corrected or normalized using θ_1 and δ_1 as follows:

Gross thrust,	$Fg/\delta 1$
Airflow,	$Wa\sqrt{\theta_1}/\delta_1$
Fuel flow,	$Wf/\delta_1\sqrt{\theta_1}$
Total temperature,	T/θ_1
Total pressure,	P/δ_1

6.1 Humidity Corrections

Engine performance is significantly affected by high humidity in the intake air. While air properties (Cp, γ, MW, R - specific heats, molecular weight, and gas constant) can be corrected for reasonably low levels of absolute humidity, high relative humidity may result in condensation in the engine inlet. The phase change from vapour to liquid in the accelerating air inflow stream results in a temperature rise in the air stream, which is difficult to handle precisely for airflow calculations. Subsequent evaporation in the fan stream reverses the process. Furthermore, wetness of fan blade surfaces may affect fan efficiency. Visible moisture in the air could also enter the pressure probes introducing biases in the pressure measurements. Thus, in order to avoid condensation in the air inlet stream, the following atmospheric limitations should be observed:

maximum relative humidity: 75%
maximum absolute humidity: 14 g water/kg air (98 grains)

The thermodynamic properties of moist air may be determined by a weighted average of the properties of the two components - dry air (subscript a) and water vapour (subscript w). Based on absolute humidity, q, in grams of water vapour per kilogram of dry air, the following equivalent dry air properties can be defined:

$$C_p = \frac{1000\ C_{p,a} + qC_{p,w}}{1000 + q} \qquad \text{(specific heat at constant pressure)}$$

$$C_v = \frac{1000\ C_{v,a} + qC_{v,w}}{1000 + q} \qquad \text{(specific heat at constant volume)}$$

$$\gamma = \frac{1000\ C_{p,a} + qC_{p,w}}{1000\ C_{v,a} + qC_{v,w}} \qquad \text{(ratio of specific heats)}$$

$$R = \frac{1000\ R_a + qR_w}{1000 + q} \qquad \text{(gas constant)}$$

This approximate method and its experimental verification is described in Reference 4. It yields corrections to obtain dry thrust and airflow at constant rotor speed, ram pressure ratio, and inlet temperature.

6.2 Fuel Flow Corrections

Jet fuel, especially the wide cut JP4 (Jet B), can range quite widely in specific gravity, and to a lesser extent in lower heating value. Data comparisons must be brought to a common base of weight and heating value. Volumetric turbine meters should be calibrated using a fluid of similar viscosity and specific gravity to jet fuel. Actual specific gravity (SG) varies with fuel temperature, therefore true fuel flow is obtained by applying a direct ratio of the actual specific gravity to the baseline test fluid SG. Similarly, fuel flow is corrected to a common base by applying a direct ratio of the heating value of the test fuel to the heating value in the model specification. A commonly accepted base for heating value is 42769 J/g.

6.3 Rake Losses

Flow path temperature and pressure rakes produce losses which reduce engine performance. Studies on particular engine marques have shown that internal rake losses, alone, could affect thrust by up to 0.7% at a constant combustor exit tempera-

ture. The effect of rake loss on engine performance can be more easily quantified analytically then empirically. One method is to use a cycle deck to establish performance derivatives for internal rake pressure.

The derivatives are multiplied by the rake loss to obtain performance increments which are then added to the measured performance to arrive at the final thrust and specific fuel consumption.

6.4 Engine Control Schedules

Simple, fixed geometry engines, operating in environmental conditions not too far removed from standard day, may adhere to the corrections as predicted by dimensional analysis. Modern high performance engines are more complex, may have two or more spools, and/or several modes of variable geometry that are scheduled as a function of several independent parameters. Performance may be predicted based on the best available component data and theory, however, experimental tests are required to establish performance deviations for temperature, pressure, Mach number, and control settings. These data, gathered from a number of engines, are used to refine predictive thermodynamic models. These models or status decks, programmed to run on a digital computer, are virtually mandatory to correct engine data collected at non-standard or off-design point conditions, back to standard reference conditions. The model includes performance maps of each component, flow areas, duct pressure losses, and engine control schedules.

When the deck is run at a given flight condition and power setting, a cycle match determines the steady-state operating point for each map, and as the flight condition changes, each component finds a new operating point on its map. Figure 7 shows how the fan operation migrates along an operating line at a given flight condition and power-setting when going from standard to non-standard day. To employ an 'average engine' status deck for data reduction of as-tested performance for a given engine, each component map and schedule is first adjusted to match the measured component performance before establishing the cycle match. Figure 8 shows an example of the way the status fan map is adjusted to match the as-tested fan performance. This process takes place with each component for each data point. By adjusting the maps to the measured information, a complete and consistant description of the engine on test is obtained, including thrust, fuel consumption, component map efficiencies and operating lines. Having matched the as-tested performance parameter, performance adjustment to Standard Day is performed by running this status cycle to the desired altitude, Mach number, ambient temperature, and control schedules in exactly the manner any status cycle is run. This is the only way that sea-level stands without any form of environmental control can compare and correlate data to any other facility.

7.0 DATA PRESENTATION

Experimental programs can produce voluminous quantities of data, especially if an automated data gathering and handling system is used. There is a great tendency to measure everything that is possible often without regard as to how the data will later be presented.

The prime purpose of a correlation program is to calibrate a test facility with another facility of known characteristic so that engine test results can be confidently accepted by either party. The most common method is to test an engine of known performance in both facilities and establish a thrust correction factor. This correction, when added to the scale force, will yield engine gross thrust. The thrust correction term can be verified by comparing the specific fuel consumption at a given level of thrust. Any differences would need to be explained by the thrust correction or a change in engine efficiency. For these reasons, gas path and fuel flow measurements are critical.

The data analysis must address the following:

1) Assessment of the uncertainties inherent in data measurement and reduction.

2) Evaluation of data consistancy within a test run and a test program.

3) Selection of appropriate engine parameters that could identify engine changes due to deterioration or external influences.

4) Calibration of the facility thrust bed and the effect of cell aerodynamic on engine gross thrust. The calibration is best achieved through a cell correlation program.

7.1 Measurement Uncertainty

Estimates of measurement uncertainty are necessary to establish the quality of data before any meaningful comparisons can be made. Measurement uncertainty is the maximum error which might reasonably be expected between a measurement and the true value defined by a National Standard.

Measurement error has two components: a fixed or bias error, and a random or precision error. The bias error is the constant or systematic error and is determined

by comparison with a true value. Through a calibration process, correction factors are generated that can eliminate or reduce large biases. Precision error, which is the variation between repeated measurements, can often be reduced by taking several repeated observations and averaging.

Overall measurement uncertainty combines the elemental bias and precision error and expresses it as a single number for a reasonable limit of error. The procedure outlined in Reference 5 can be followed to generate values of bias and precision errors for each measurement. Calibration, data acquisition, and data reduction error sources can be combined in a root-sum-square method to yield overall uncertainty limits.

Related to measurement uncertainty is the method of data display. Discrete data points are gathered, usually as a function of power setting (rotor speed or engine pressure ratio), and printed out as discrete numbers or plotted on graphs. To quantify the data scatter and provide a means of data comparison, data should be curve fit against an appropriate independent parameter. One method employed at NGTE (Ref. 6) fits the data using a least-squares quadratic equation and provides an estimate for the curve fit random error limit (RELCF). The RELCF quantifies the data scatter about the fitted curve. By comparing the RELCF to the estimated precision errors, as described above, instrumentation problems or engine instability can be detected.

7.2 Engine Cycle Matching

Small changes in engine performance may be caused by external effects, component deterioration, or control system repeatability. Indicators of engine health are the ratio of spool speeds on multi-spool engines, compressor efficiency, and overall engine pumping capacity.

Inflow pressure distortion affects the radial work distribution across the compressor. The expected result would be a change in compressor efficiency, affecting fan engines to a larger degree than turbojets. If the distortion is severe enough, there may also be a shift in the ratio of spool speeds on multi-spool engines. For example, a poorly designed bellmouth may create sufficient flow distortion to cause the engine to rematch. Figures 9 and 10 show typical plots of rotor speed ratio and compressor efficiency as functions of high pressure rotor speed. Compressor efficiency was calculated from pressure and temperature obtained with rakes inserted in the compressor exit stream. The upper curve in both figures represents the case with a relatively flat inlet pressure profile, whereas the lower curve is the case with a thick boundary layer. Implied in the comparison is that the compressor is clean, and variable geometry, if any, is operating on the same schedule. Since the inflow distortion effects are difficult to quantify, a common bellmouth and inlet section is strongly recommended when correlating test facilities. In addition, a high response pressure transducer could be installed to quantify and monitor turbulence levels.

Overall engine health can be assessed by examining the engine pumping capacity. If the engine is thought of as a pump wherein a given overall engine pressure ratio (EPR), requires a given level of energy input defined by fuel flow or engine temperature ratio (ETR), a plot of EPR against ETR can be interpreted as a measure of overall engine efficiency. However, the requisite tailpipe pressure and temperature sensors may not be available in some engines.

Furthermore, the location of the probes, whether part of the engine control system or installed especially for the test series, may not sample the average thermodynamic properties due to position errors and flow gradients. A theoretical turbine exit temperature could be calculated based on fuel flow and an energy balance across the compressor and combustor. A reference value of pressure is still required, but for a comparative assessment even a tailpipe wall static would suffice.

The above information can also be used to establish data consistency. Over small ambient temperature ranges, the compressor and engine pumping data should be within the measurement uncertainty limits. Other methods of checking data consistency are:

1) By comparing measured exhaust nozzle flow and thrust characteristics with experimental data (ASME or NASA reports).

2) By calculated/measured turbine nozzle flow functions for several power settings where the nozzle is choked.

3) By measuring pressure and temperature profiles at the engine inlet, and if possible, at the compressor exit and exhaust nozzle inlet.

Data falling outside the limits would point to instrumentation problems, engine non-repeatability, or an incorrect error analysis.

7.3 Engine Performance

Engine performance generally refers to net thrust and specific fuel consumption (SFC). Airflow, another performance parameter, is very useful for diagnosing engines of low thrust.

Model specifications define acceptable performance levels as:

1) Specific fuel consumption equal to or less than specification level plus the predicted tolerance band.

2) Thrust equal to or greater than the specification level minus the predicted tolerance on thrust.

This is depicted graphically in Figure 11. The specification point is defined for various values of altitude and Mach number. Within the measurement tolerances, provided that engine net thrust is greater than, and SFC is less than the specification point, the engine meets the guarantee. Should an engine fail to meet this target, individual engine parameters need to be examined.

There is no agreed upon standard independent parameter against which to compare engine data. One facility may prefer high pressure rotor speed, another low pressure rotor speed, and a third engine pressure ratio. The rationale for choosing a rotor speed to plot all parameters becomes weak when a noticeable split in rotor speed ratio, due to an external influence, occurs between facilities. Rather than plotting all performance data against a single parameter, the following section outlines suitable relationships.

7.3.1 Airflow

Airflow measurement in the inlet duct using local measurements of pressure, temperature, and area was described in section 4. Other locations in the engine such as the turbine nozzle or final nozzle in a non-afterburning engine could be used provided the actual areas were known. Afterburning turbofan engines are more difficult to deal with as the variable nozzle area must be known. However, a knowledge of bypass flow determined by local pressure, temperature, and area measurements, combined with turbine nozzle flow would yield a flow measurement.

A knowledge of the fan characteristics could provide another check. The inlet non-dimensional flow function of any fan or compressor can be expressed as a function of non-dimensional shaft speed and pressure ratio, and for turbofan engines, the bypass ratio:

$$W\sqrt{T}/P = f(N/\sqrt{T}, PR, BPR)$$

With a knowledge of fan speed, pressure ratio, and bypass ratio, inlet flow can be derived. Inlet flow distortion, Reynolds number, inlet temperature, and variable geometry affect the fan characteristics and must be accounted for.

Since airflow to the engine is set by the fan or low pressure compressor, airflow should be plotted against the low rotor speed. An example is shown in Figure 12.

7.3.2 Fuel Flow

Fuel flow checks normally consist of comparing fuel flow between redundant flow meters. The differences should fall within measurement uncertainty limits.

Fuel flow is a function of airflow to maintain a scheduled fuel/air ratio. As airflow is determined by the low pressure compressor, fuel flow should be plotted against low pressure rotor speed.

Consistency checks involve comparing fuel flow against measured or calculated turbine discharge temperature and turbine discharge pressure. These functions are indicative of overall engine efficiency as discussed in the section on cycle matching.

7.3.3 Thrust

Thrust is directly proportional to engine mass flow and jet velocity for an unchoked exhaust nozzle, and is modified by a pressure term when choked. Engine mass flow is a function of the LP rotor speed, while nozzle exit velocity is a function of nozzle pressure ratio. It is therefore logical to plot engine thrust against both LP speed and nozzle pressure ratio. Since LP speed is sensitive to cycle matching, the accepted practice is to relate thrust to nozzle pressure ratio.

Going one step further, nozzle characteristics can be described by two methods, one called $W\sqrt{T}$ function and the other the FAP function. The first method uses a parameter formed from the measured gross thrust, Fg, by dividing it by engine inlet airflow, Wa, and nozzle entry temperature, T7. The second parameter is gross thrust divided by nozzle area, A8, and either the nozzle entry pressure, P7, or the local ambient pressure, Pamb. Thus,

$$\frac{Fg}{Wa\sqrt{T7}} \quad \text{and} \quad \frac{Fg}{A8 \cdot P7}$$

The FAP function contains the smallest measurement uncertainty, especially for a fixed nozzle engine. The $W\sqrt{T}$ option, because of the uncertainty in T7 tends to be less accurate. In a mixed stream nozzle, T7 is difficult to measure and must be calculated. Of

the two, the FAP function has the least sensitivity to performance changes in the gas generator. Neither airflow nor fuel flow measurements are required, but a knowledge of nozzle area is needed. Plots of both thrust coefficients are shown in Figures 13 and 14. Better agreement is obtained using the same engine data when expressed as the FAP rather than the $\sqrt{T}$ coefficient when plotted against nozzle pressure ratio.

Another method of data comparison, that can also provide relative checks on airflow and thrust, is to examine exhaust nozzle performance. Based on temperature and pressure measurements at the nozzle entry plane, Station 8, and knowing the nozzle area, A8, ideal values of airflow and gross thrust can be calculated. Facility measured values of airflow (Wa) and thrust (Fg) are divided by the corresponding Station 8 ideal vaues to yield flow (CD8) and thrust (CG8) coefficients.

CD8 = Wa/WaI8
CG8 = Fg/FgI8

CD8 = flow coefficient
CG8 = thrust coefficient
Wa = facility airflow
Fg = measured gross thrust
WaI8 = ideal airflow, Station 8 = f(γ,R,P7,T7,A8,Pamb)
Fg = ideal nozzle gross thrust = f(γ,P7,Pamb,A8)
A8 = nozzle area corrected for thermal expansion

The flow and thrust coefficients are plotted as functions of nozzle pressure ratio, P7/Pamb in Figures 15 and 16. Values of CG8 and CD8 should be less than unity. The curves may be compared against model data (Ref. 7) for general shape, however due to three-dimensional effects and a non-uniform flow field in the test data, the actual values of coefficients may not agree.

Having arrived at a credible value of thrust and fuel flow, specific fuel consumption (SFC) is obtained by dividing thrust by fuel flow. It is a measure of engine efficiency and is a key performance parameter. Plotting SFC against net thrust (Figure 17), the target specification point can be compared to (Figure 11). If the curve lies below the target value, the engine meets acceptance.

7.4 Cell Factor

The cell factor is the ratio of actual gross thrust to the measured scale force at the tested inlet and exhaust conditions. This factor accounts for the drag forces resulting from engine operation in a test cell and it also compensates for any systematic scale force measurement errors. The cell factor, accurately established using the FAP function, corrects the thrust to the as measured inlet temperature and Mach number, defined by inlet conditions and tailpipe ambient pressure. A typical cell factor is shown in Figure 18. It is plotted as a function of nozzle pressure ratio, and ranges from a correction of near 7% at low power settings to 2% at high power settings. The cell factor is valid only for a particular engine type and cell geometry. Significant geometry changes to either the inlet or exhaust section, or a repositioning of the engine would require a new cell correlation.

8.0 CONCLUDING REMARKS

Sea-level test cells, despite their limitations on environmental control fulfill an important role in assessing engine performance. Enclosed test cells require a number of corrections to the measured value of thrust to obtain an uninstalled gross thrust. These corrections, commonly lumped together and called a cell factor, are established by correlating the facility to some standard datum. The universally accepted datum is an outdoor test stand, which when utilized in conditions of zero wind, measures gross thrust directly as the scale force. The correlation is effected by testing a well-instrumented engine of known repeatable performance back-to-back on the outdoor and then the indoor stand. The difference in scale force thrust, corrected to standard day conditions, between the facilities is called the cell factor. Thus, gross thrust for the indoor stand is obtained by adding the cell factor to the scale force.

Engine health must be monitored during the correlation process, as the results would be invalid should the engine show significant deterioration. Compressor and overall engine efficiency can be monitored by pressure and temperature measurements in the gas stream.

Nozzle thrust coefficients as a function of nozzle pressure ratio were shown to be the best cell correlation parameters as they are not overly sensitive to shifts in gas generator performance.

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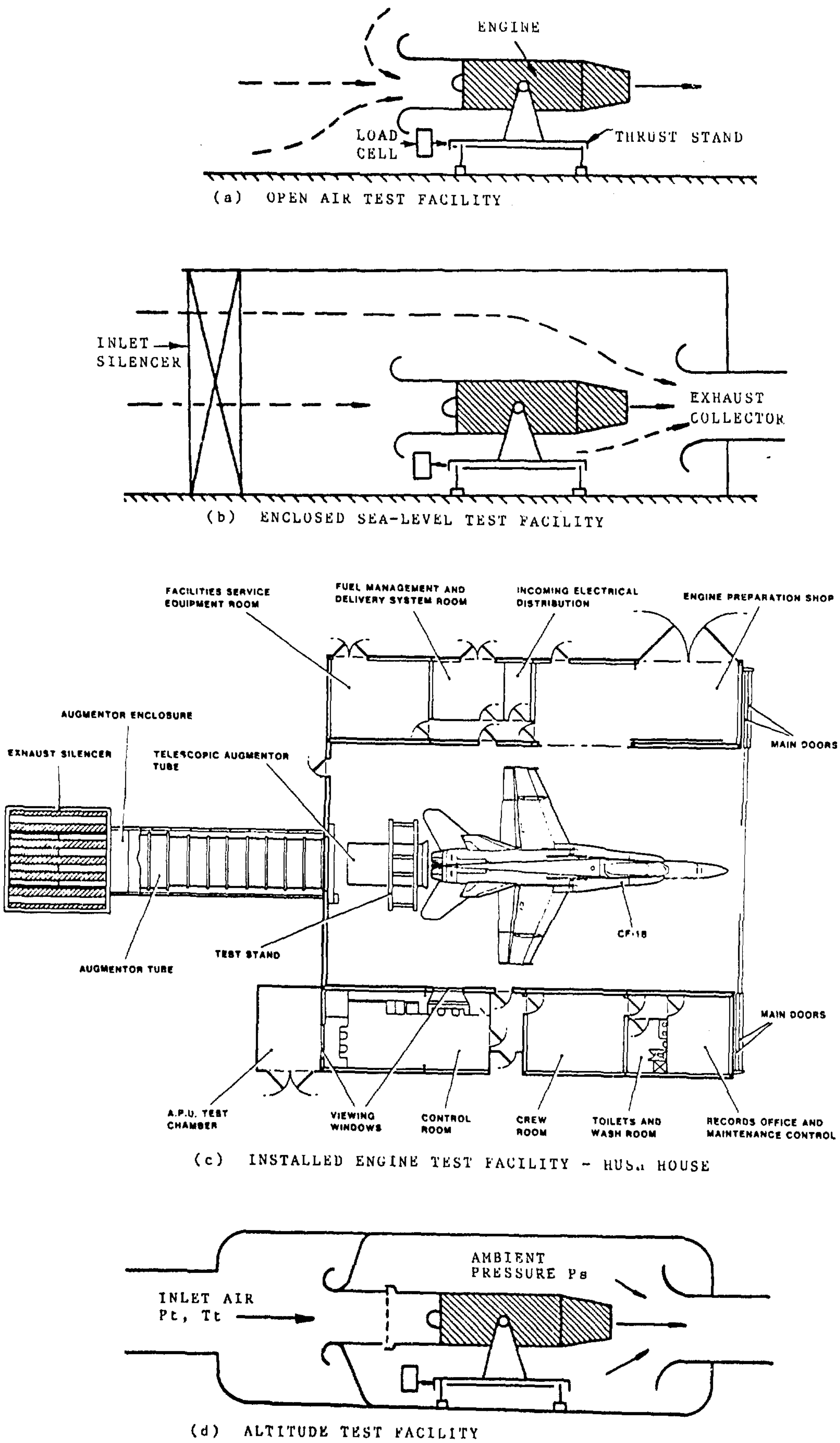

FIGURE 1 ENGINE TEST CELL ARRANGEMENTS

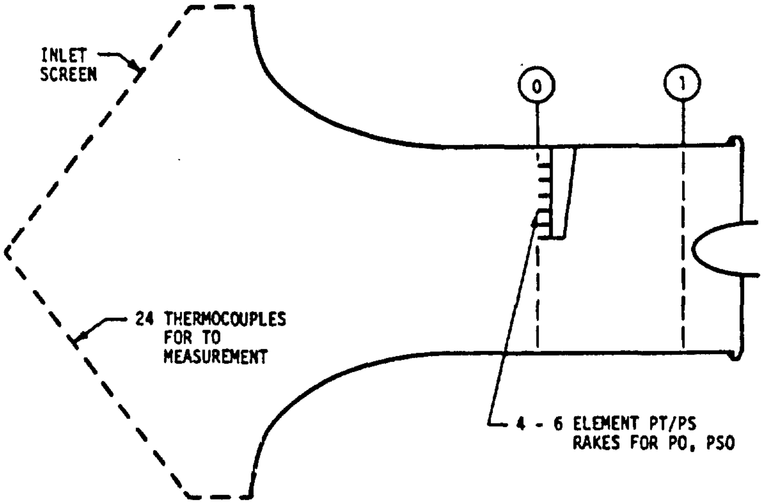

FIGURE 2 BELLMOUTH FLOW MEASUREMENT SYSTEM FOR SEA-LEVEL CELLS

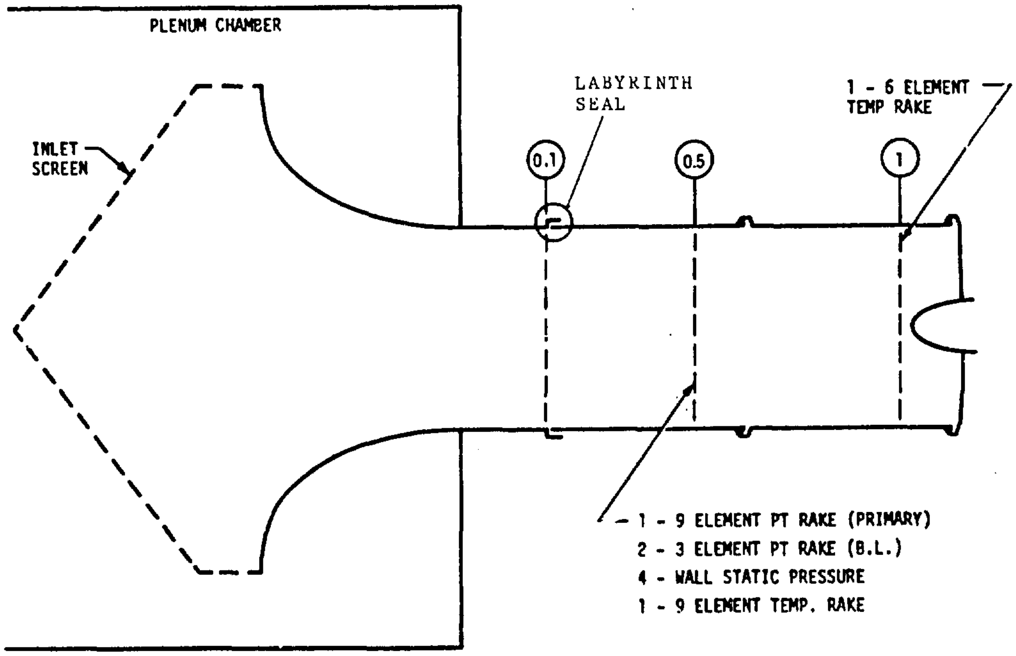

FIGURE 3 AIRFLOW MEASUREMENT SYSTEM FOR ALTITUDE CELLS

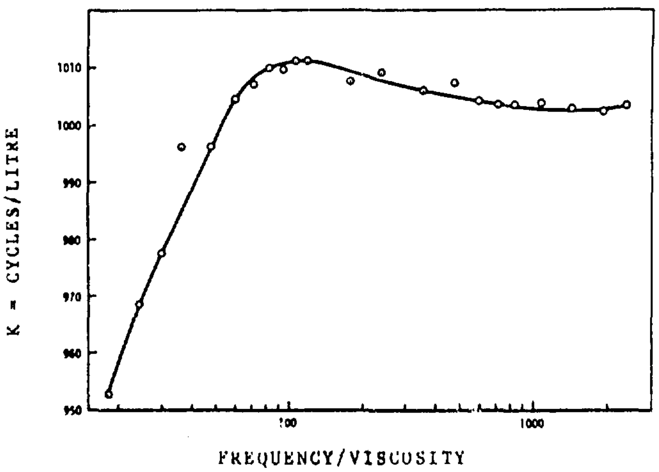

FIGURE 4 TYPICAL FLOW SENSOR CALIBRATION

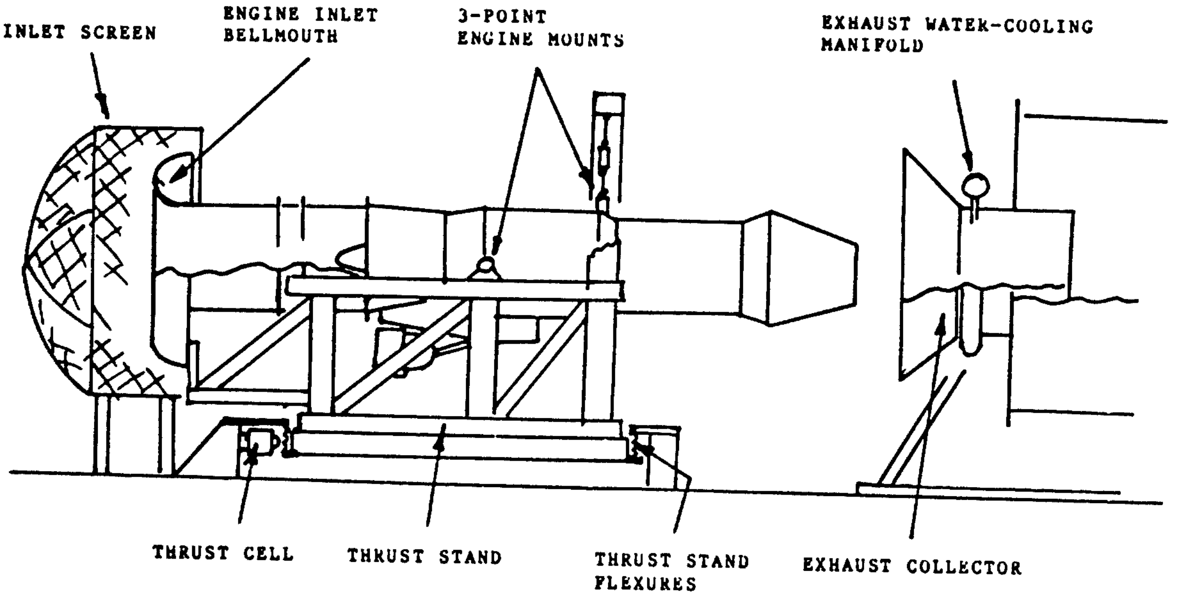

FIGURE 5 ENGINE INSTALLATION ON A THRUST BED

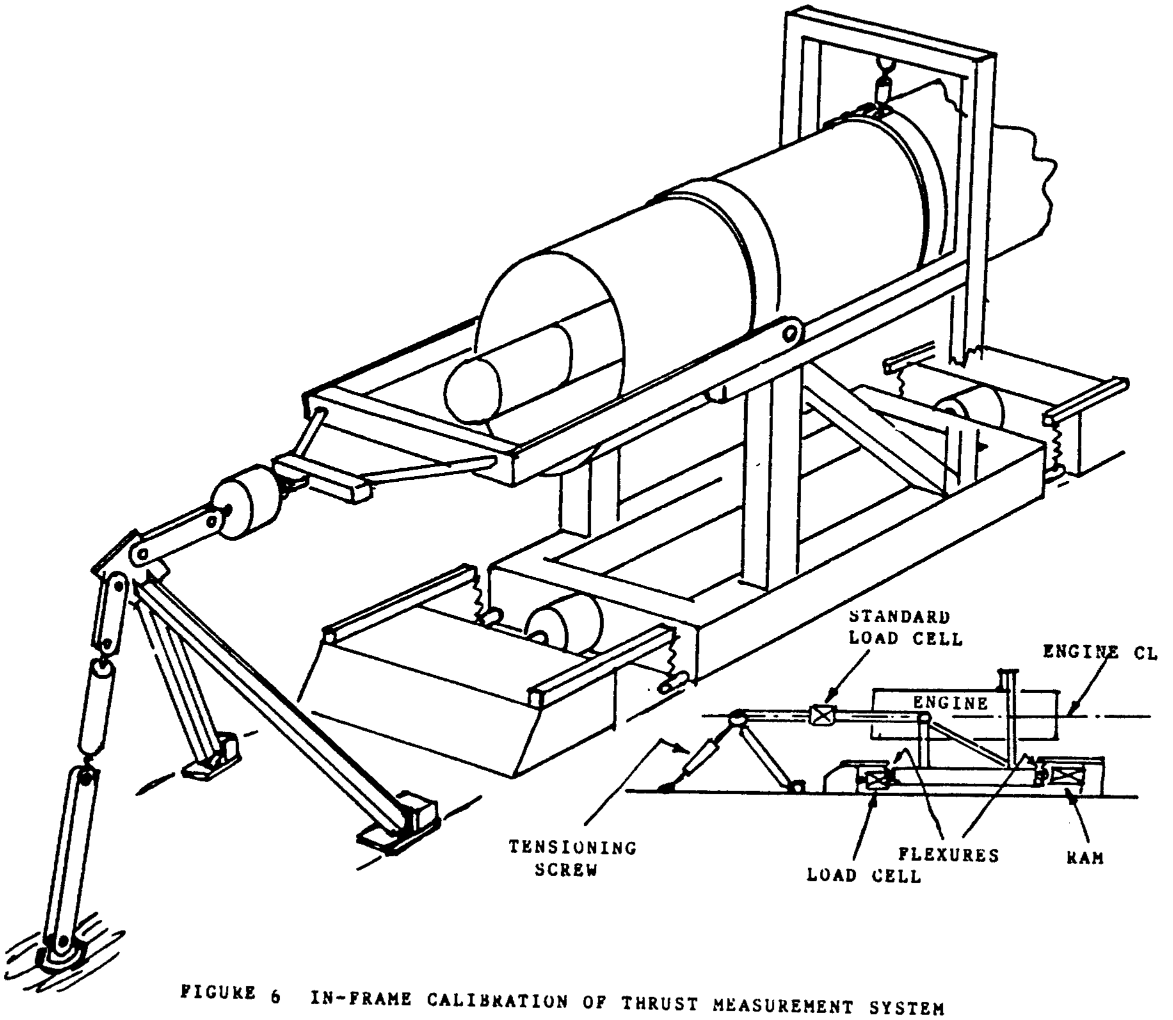

FIGURE 6 IN-FRAME CALIBRATION OF THRUST MEASUREMENT SYSTEM

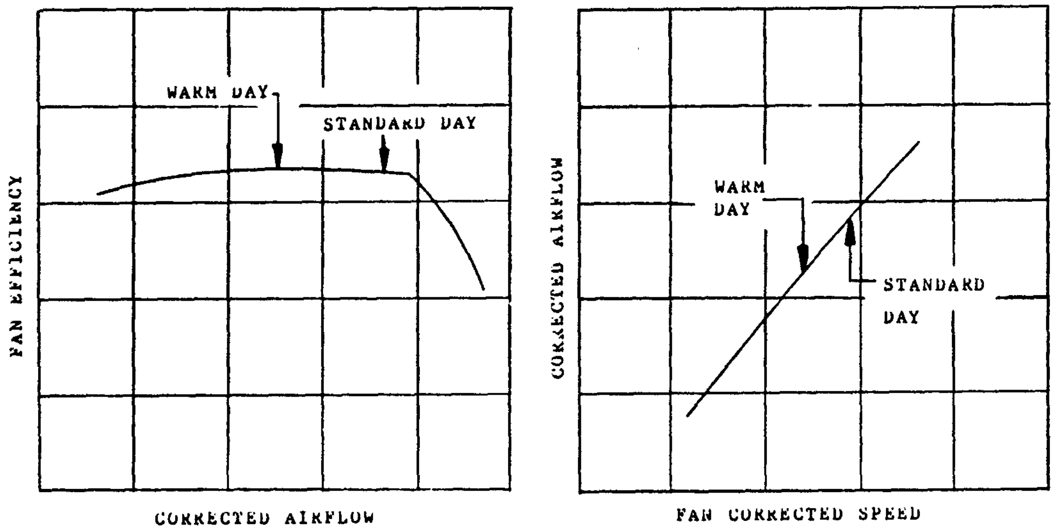

FIGURE 7 STATUS DECK - COMPONENT PERFORMANCE STANDARD - NON STANDARD DAY

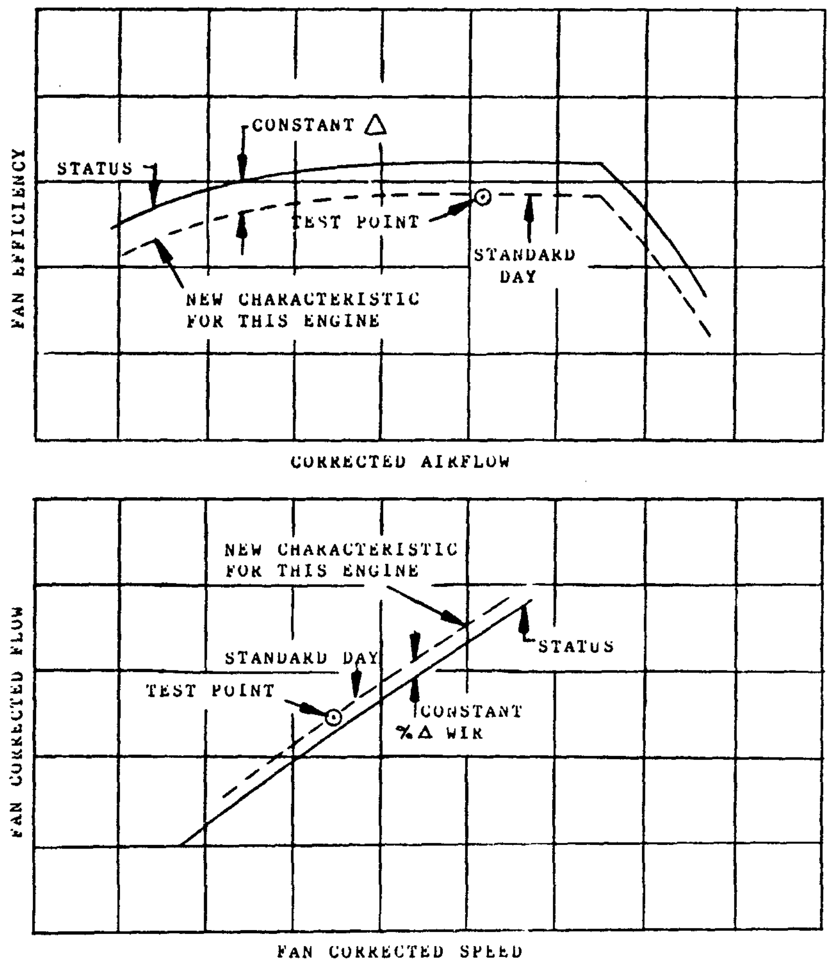

FIGURE 8 STATUS FAN MAP VS AS-TESTED FAN PERFORMANCE

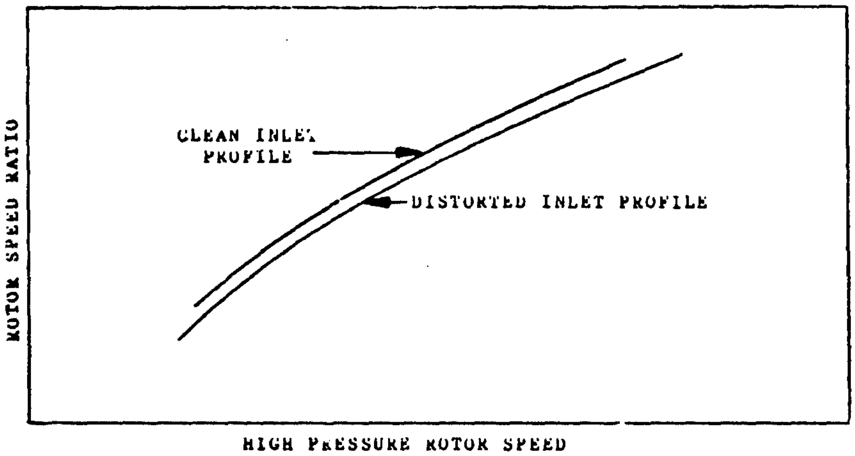

FIGURE 9 ROTOR SPEED RATIO VS HP ROTOR SPEED

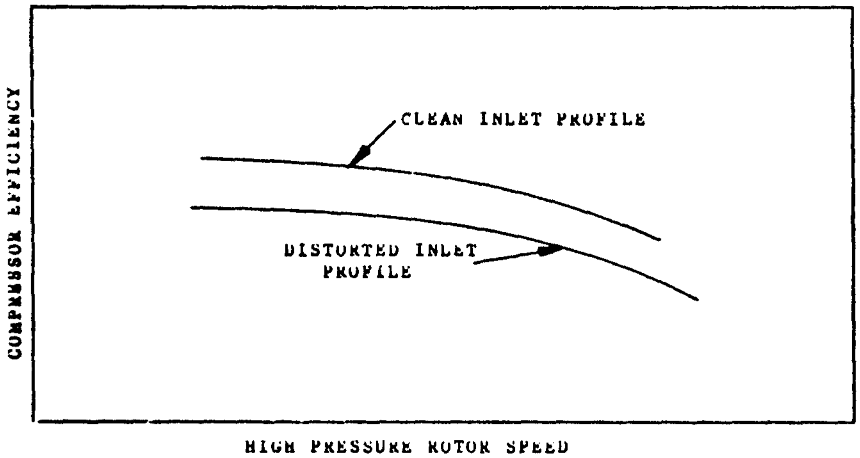

FIGURE 10 COMPRESSOR EFFICIENCY VS HP ROTOR SPEED

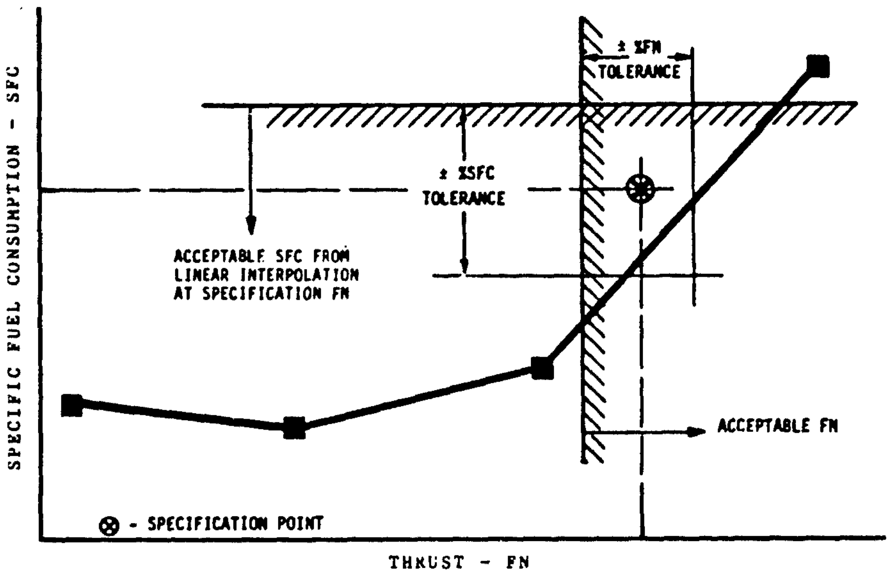

FIGURE 11 PERFORMANCE SPECIFICATION

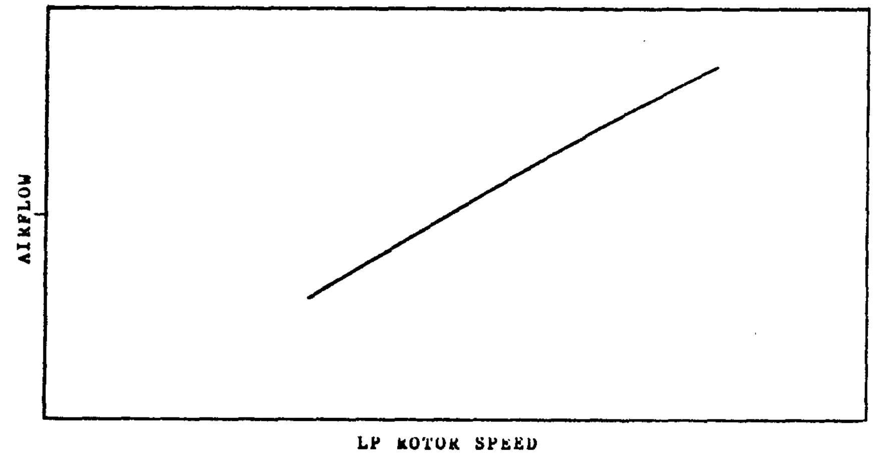

FIGURE 12 AIRFLOW VS LP ROTOR SPEED

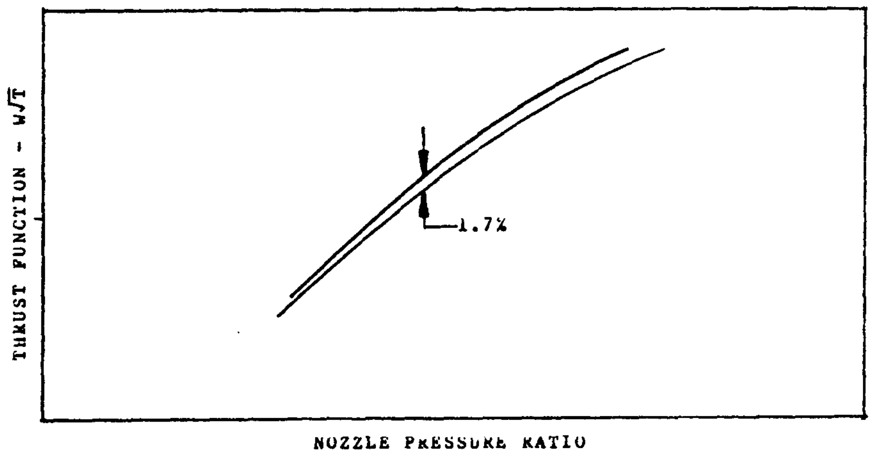

FIGURE 13 THRUST FUNCTION VS NOZZLE PRESSURE RATIO

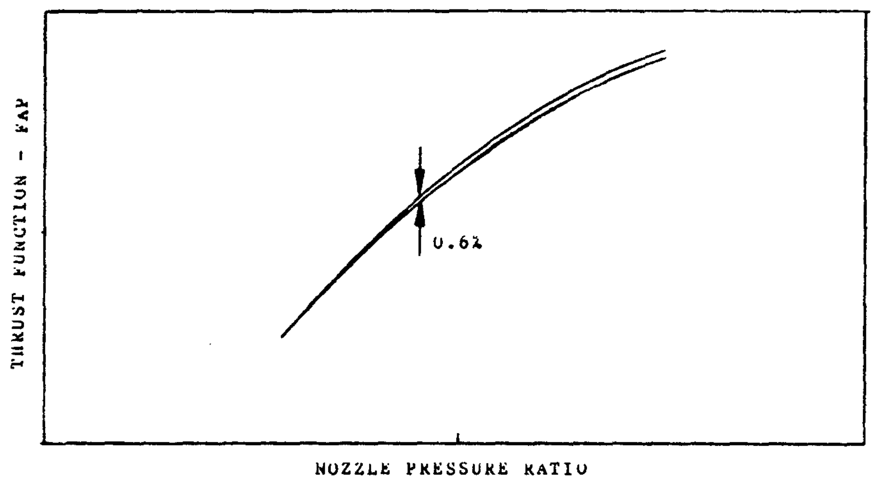

FIGURE 14 THRUST FUNCTION VS NOZZLE PRESSURE RATIO

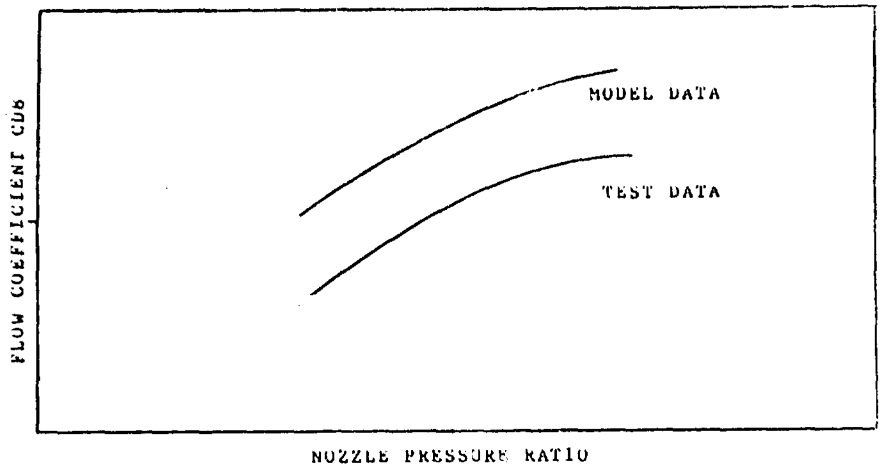

FIGURE 15 CD8 VS NOZZLE PRESSURE RATIO

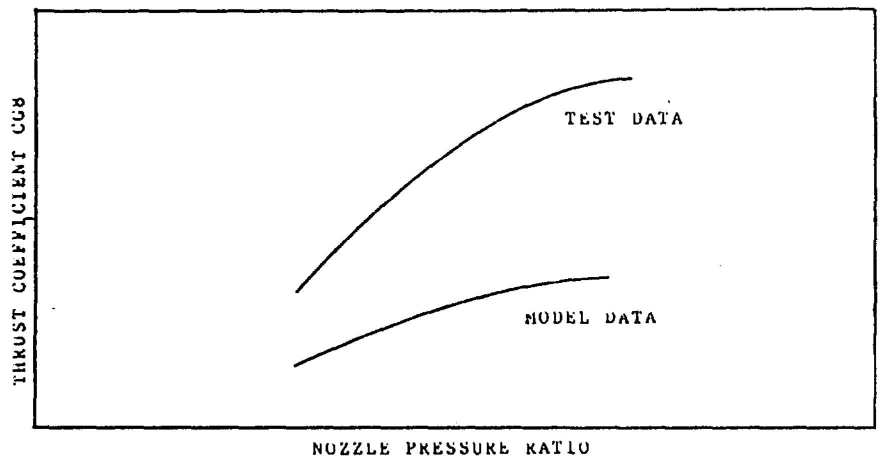

FIGURE 16 CG8 VS NOZZLE PRESSURE RATIO

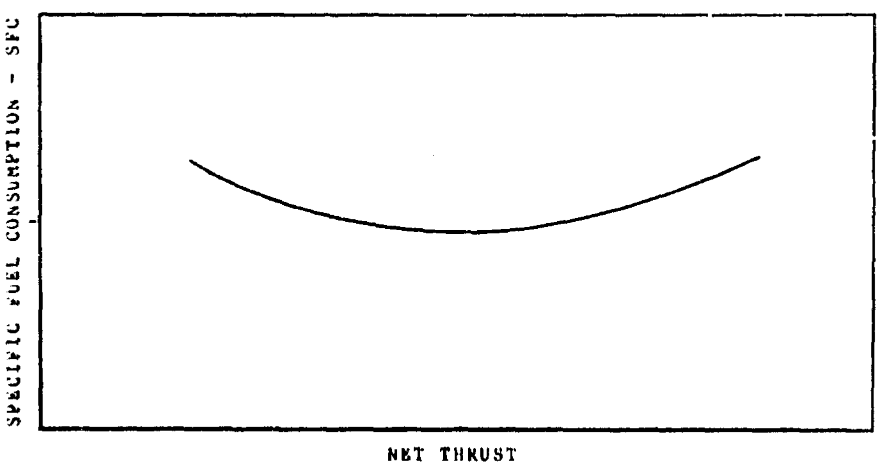

FIGURE 17 SFC VS NET THRUST

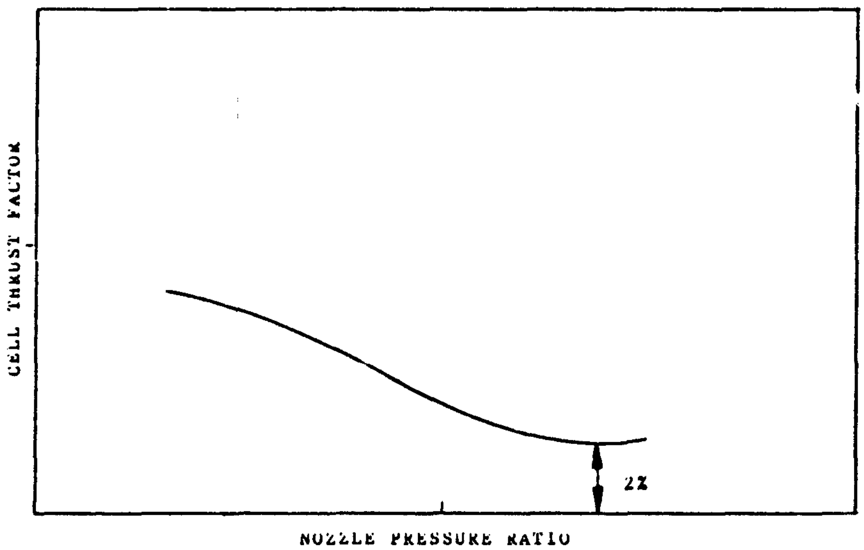

FIGURE 18 CELL FACTOR VS NOZZLE PRESSURE RATIO

TESTING OF TURBOSHAFT ENGINES

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SUMMARY

Safety in flying is of paramount importance. The high standard of the theoretical principles behind research and design and quality measures during production on their own are not sufficient for guaranteeing adequate safety. Therefore testing of components and engines before installation in aircraft is still required.

It may prove possible to reduce the extent of testing, based on more sophisticated evaluation methods and testing techniques. Modular designed engines may be tested even less in the future, if the effect of specific replaced modules is well understood.

Testing is one of the main features of engine development, manufacturing and maintenance. This lecture is concerned with this subject and, in the time allowed, I shall go into two main aspects of it:

- Design and installation of test facilities for turboshaft engines, and the
- Carrying out of test runs and their evaluation.

1. INTRODUCTION

In the days when flying was still in its infancy, the testing of aircraft engines was a relatively uncomplicated affair. The engines were simply mounted on pedestals and the torque was determined by a primitive pendulum system and weights. Instrumentation was minimal, where the human ear was the main instrument for judging abnormal running of the engine.

The requirements made of test facilities have grown correspondingly with the increasing complexity of the engines and extreme requirements for performance, weight reduction, reliability, safety and ease of maintenance by the use of the modular concept.

In the computer age and with increasing environmental consciousness, the fulfilment of these requirements to an appropriate standard by modern engine test facilities is taken for granted. That this has been achieved has been demonstrated in many cases.

2. DESIGN AND INSTALLATION OF TEST FACILITIES FOR TURBOSHAFT ENGINES

Regarding the first aspect, there are two ways to design an engine test facility:

- Open-air test facility, and
- Enclosed test facility

An open-air test facility can be installed at relatively low cost, and thus provides a simple and economical method of engine testing. Moreover, it is easier to carry out special tests simulating flight conditions or nacelle tests, for example, than with an enclosed facility.

On the other hand, there are considerable disadvantages, namely

- Noise nuisance, caused by engine and propeller
- Meteorological conditions can limit the availability of the facility or have a negative effect on the engine behaviour, making it impossible to assess the engine's performance accurately
- Protection against foreign object ingestion is very poor
- Unsatisfactory conditions for the installation and operation of test and control systems
- Laborious handling of engines and test equipment
- Shortage of utilities

All these arguments have to be taken into consideration in the planning and installation of an open-air test facility.

2.2 SYSTEM LAYOUT OF A TURBOSHAFT ENGINE TEST FACILITY

As already pointed out, the design and function of the test equipment differs widely, depending on the type of engine undergoing tests and the purpose of the tests.

Fig. 2 shows the typical layout of a test facility intended for acceptance tests following manufacture or complete overhaul of turboshaft engines. It consists of the following main components:

- Test cell, control room, supporting rooms, prerigging area/preparation shop
- Sound treatment
- Supply systems for electrical power, fuel, starting and supply air, cooling water
- Engine loading equipment
- Facility control system
- Engine control system
- Signal conditioning system
- Data acquisition and processing system (hardware and software)
- Safety features (fire-fighting and ventilation systems)
- Special-to-type engine equipment
- Junction lines

Just from this rough listing of the components which constitute the facility it can be seen that the planning and construction of a test facility involves a wide range of industrial technology.

The most important criterion in designing such facilities is one hundred percent compatibility of the individual components. The designer must never forget:
The test bed is merely a tool for the test engineer, that is to say a means to an end. The test engineer's problem lies with the engine, not with the test facility.

I would now like to go into some criteria important for the design of components of a typical turboshaft engine test facility.

2.2.1 BUILDING

In comparison with test facilities for jet engines, particularly large turbofans, the requirements regarding the design of the building represent few problems; although a difference has to be made between turboshaft engines loaded by a dynamometer and turboprops by a propeller.
In the later case, a difference is made between three variants:

- L-shaped test cell
- U-Shaped test cell, and
- Straight-through test cell

All three versions are acceptable from the aerodynamic point of view; but whereas the straight-through type is said to exhibit better characteristics with regard to reducing air turbulence, many designers feel that this is compensated in the other types by a more optimal vane arrangement.

On the whole, I find that the L-shaped cell, i. e. horizontal air intake and vertical exhaust section, is the best, since it combines the advantages of horizontal flow to the engine and reduced nuisance of smell and noise in the vicinity of the test facility.

In general, the following criteria need to be taken into account when designing the building complex:

- Position in relation to the other buildings and to the supply systems
- Allocation of supporting rooms
- Avoidance of acoustical and vibrational problems by isolating different sections of the building
- Maintenance of short transfer routes, optimum routing of supply and instrumentation lines, communications systems
- Safety requirements

2.2.2 NOISE CONTROL

The following noise control measures and equipment are required for the protection of the test cell personnel and the environment:

- Intake stack sound treatment
- Exhaust stack sound treatment
- Soundproofed doors and observation window
- Isolation of building sections to prevent transmission of structural noise, as well as acoustic baffles for interconnecting ducts

As a rule, noise criteria are laid down in relevant specifications, but the following may be taken as approximate values:

- Test cell environment: 60 dB(A) at 100 metre distance
- Control room: less than 65 dB(A)
- Prerigging area: less than 70 dB(A)
- Other rooms: less than 85 dB(A)

The acoustic design of the sound treatment depends greatly on the type of test facility, that is to say on whether testing is carried out with a propeller or brake.

Depending on the speed and number of blades of the propeller, frequencies of around 40 Hz at a sound level of up to 130 dB(A) occur.

It is much simpler and cheaper to design corresponding sound treatment for test facilities connected to a dynamometer.

Over and above this, the following criteria must be taken into consideration when designing the sound treatment:

- Prevailing climatic conditions, which might give rise to corrosion problems
- Pressure losses
- Operation of the facility during daytime/nighttime
- Maintenance requirements and durability
- Exhaust gas temperature

The sound treatment represents a major cost factor in the setting up of a test facility. Accordingly, appropriate attention must be paid to the design and construction in order to achieve optimum effectiveness, even though these components do not actually have a positive influence on the testing itself.

2.2.3 ENGINE LOADING SYSTEM

As already mentioned, before planning the test facility, the method of absorbing the shaft horsepower developed by the engine must be decided. This decision will result in the design and construction of either a propeller- or dynamometer-type test cell.

Because in this paper we are mainly concerned with the testing of turboshaft engines, in other words engines for helicopters and fixed-wing aircraft, we shall confine ourselves to the loading system that covers both cases, that is to say the dynamometer-type.

The brake system forms the cornerstone of a test facility for turboshaft engines. It applies the load to the power turbine and absorbs the power of the engine. Appropriate instrumentation allows the torque to be determined.

Diverse devices are used for loading turboshaft-engines, for example:

- Cradle dynamometers
- Air compressors
- Hydraulic dynamometers (water brakes)
- Eddy-current dynamometers

The commonest types in use are water brakes and eddy-current dynamometers.

The water brake (Fig. 3) consists of a rotor system rotating between a stator. Water is fed into the rotor chambers and is thrown outward against the stator by centrifugal force. The water forms a ring, in which the rotor is constantly rotating. As the rotor accelerates the water the stator decelerates it, resulting in a shearing action. The reaction force on the stator tries to turn the water-brake housing, which is mounted on trunnion bearings, creating a moment, which can be measured by a load cell.

The choice of a suitable measuring system (mechanical, pneumatic, hydraulic or electrical) depends on the accuracy requirements and on the general conditions of the facility.

The mechanical layout of the eddy-current (Fig. 4) dynamometer is similar. In this case, however, the braking effect is obtained by the rotor cutting through an eddy-current field. This field is generated in an excitation coil in the stator via a non pulsating impressed direct current. Water is passed through the machine simply to remove the equivalent heat.

Depending on the type of test to be performed, different load-control systems have been designed (Fig. 5), such as:

- Propeller law
- Constant speed
- Constant torque

The first two systems mentioned are entirely sufficient for the testing of turboshaft engines.

When choosing a suitable braking system, the test cell design engineer has to consider other criteria, such as:

- Water supply conditions
- Response-time for load changes
- Operating range of the dynamometer (Fig. 6)
- Moment of inertia
- Durability
- Maintenance
- Weight and dimensions

2.2.4 ENGINE HANDLING

The system chosen depends greatly on how many engines of the same or even different types require to be handled. The objective is obvious:

To achieve a minimum of turnover time and a maximum of test bed availability.

Various methods are used for attaining these objectives.

The engine to be tested will be installed in a special-to-type suspension unit and is prepared for test in the prerigging area. It is then moved into the test cell by trolley or monorail crane. The supply and instrumentation systems of the test facility are connected to the suspension unit by means of quick-release couplings.

If requirements are even stricter, or if several engines of different types are to be tested in the same cell, the dynamometer can also be integrated in the prerigging system.

2.2.5 SIGNAL CONDITIONING, DATA ACQUISITION AND PROCESSING SYSTEM (Fig. 7)

The technical possibilities in this area have changed and improved appreciably over the last few years. In a relatively short period, the transition has been made from analogue-digital measuring systems with unaided evaluation to fully computerized data monitoring systems.

The relevant software offers a wide-ranging assortment of processing and investigation programs. Such systems offer important advantages with regard to economy and quality, such as:

- Fuel savings
- Reduction in number of test-stand personnel
- Immediate availability of standard-day values
- Rapid comparison of actual and specified conditions, resulting in shorter running times and earlier recognition of engine defects
- Better assessment of engine behaviour thanks to greater accuracy, exclusion of reading errors and miscalculations, measurements free from timing errors
- Actions of operator and test procedure monitored by control programs, alarm programs, plausibility checks
- Improved documentation of test results, including for further statistical processing

2.2.6 ACCEPTANCE AND CALIBRATION OF TEST FACILITY

Calibration is necessary after installation of the facility, after major changes to the test cell and also whenever a new type of engine is mounted in the cell. As the calibration is of great significance for all the engines that are to follow, it must be carried out with the utmost care and accuracy.

As a rule, acceptance proceeds as follows:

- Inspection of the installation
- Function test
- Static calibration of the instrumentation
- Function run with engine
- Correlation run with calibrated engine

To enable the hysteresis and reproducibility to be checked, the correlation run ought to take the form of a double-run, that is to say it ought to involve the stagewise increase and decrease of the power throughout the range of the engine.

3. PERFORMANCE OF TEST RUNS FOR ENGINE PRODUCTION AND OVERHAUL

The test programmes are normally set by the engine manufacturer in consultation with the relevant authorities, bearing in mind the characteristics and criteria of the engine in question. In principle, however, all test programmes can be divided as illustrated in Fig. 8:

- Operational test
  To ensure that the engine operates safely within its limits.
- Performance test
  To verify the guaranteed power, fuel consumption and oil consumption figures. With turboprop engines, this includes the plotting of a performance curve against a variable power-turbine speed (e. g. 70, 90, 95, 100%).
  With helicopter engines, the performance is checked against a constant power-turbine speed.
- Leakage test
- Preservation run

3.1 PERFORMANCE CALCULATION

The engine characteristics, such as power, specific fuel consumption, speeds, temperatures, pressures, etc., are corrected to relate them to the International Standard Atmosphere (ISA - 15 °C, 760 mm Hg, humidity nil at mean sea-level).

Only after this correction can the result be assessed accurately and the individual engines compared with one another. However, it must be admitted that the importance attached to this correction to ISA conditions differs according to the engine manufacturer. For example, the one manufacturer considers the humidity of the air to be important, whereas another manufacturer ignores the humidity, taking the calorific value of the fuel to be of significance instead. Such differences can be found with virtually all correction factors.

One parameter that is essential in the assessment of all engines is the power. Fig. 9 shows a computation formula that contains a test bed factor. Whilst the factor for jet engines depends on the flow conditions through the test cell, with turboshaft engines it is derived from friction and gear losses.

Fig. 10 shows a typical evaluation sheet from a test run for helicopter and turboprop engines.

3.2 SPECIAL TESTS

Finally on this aspect, let me mention some typical tests in more detail:

- Propeller Interconnection and Full Reverse tests
  These are typical tests for turboprop engines. The objective is to ensure that the propeller governor functions properly. A typical load/speed interconnection curve is shown in Fig. 11.
  If the test cell being used is provided with a dynamometer, a special control system will be required.
  In the full reverse test, power (approximately 25%) is applied in an engine condition below idle for checking the engine/governor behaviour under reverse thrust.

- Water-Methanol test
  The water-methanol system is used on many engines for boosting the power during take-off. A water-methanol mixture (in the ratio of approximately 56 : 44%) is injected upstream of the LP compressor, increasing the power output by about 20%. This system also has to be tested.

- Acceleration Test
  In this test, turboprop engines are accelerated from Flight Idle to Take-Off speed within a few seconds. With helicopter engines the load is applied suddenly at constant power turbine speed.

- Autorotation Test
  This test is required with helicopter engines and is intended for verifying the overspeed protection of the engine.

3.3 REJECTION OF ENGINES

Engines are not uniformly good and free of defects on acceptance testing. If problems which cannot be eliminated within the test bed occur, the engine in question must be rejected and returned to the assembly line.

As mentioned earlier, the emphasis with regard to the equipping and engineering of production test stands lies in trouble shooting.

As a matter of principle, no engine should be rejected from the test stand without proper identification of the trouble and its cause.

If the trouble and its cause remain unidentified, not only will this mean higher production costs because of additional work on repeated assembly and disassembly, but there will be a danger that the test engine will be returned to the test bed affected by the same defect.

With engines whose performance is only just within limits or engines which have to operate within very close limits, it is essential that not just any modules are assembled, but that the modules are carefully selected and coordinated. For example, the LP compressor should be matched to the HP compressor, or the compressor to the turbine cross-section.

4. ENGINE DEVELPOMENT

The requirements regarding test equipment and test procedures for engine development differ according to the job in hand.

In the initial phase, it is not complete engines that are tested, but main components such as gas generator, free power turbine, combustion chamber and accessories. The purpose of this is to coordinate the components so that they will not have undesirable effects on one another and to permit problems to be pinpointed to their source.

The procedure with the main components as well as complete engines can be divided into three main stages:

- Mechanical tests
  For example, of the oil supply system, the vibration characteristics, or the cooling systems
- Thermodynamic tests
  By compatibility tests of the modules and performance determination by thermodynamic calculations, accompanied by appropriate optimization

  Already at this stage, the results provide sufficient information to permit assessment of the wear characteristics and to draw up inspection specifications and overhaul procedures
- Determination of limiting values
  Aimed at ascertaining power reserves and estimating the life of the various components

After the components have been assembled into a complete engine, the compatibility tests and optimization can commence.

There are still a number of extensive tests that have to be carried out before a turboshaft engine has been proved sufficiently. Some of these are:

- Altitude tests
- Cycle tests
- Endurance tests
- Ingestion tests
- Anti-icing and bleed tests
- Emission tests

The time required for testing up to provisional flight certification may be taken to be approximately 1,000 hours, with another 5,000 hours or so required until final flight certification. The total time required lies in the region of five years.

5. FUTURE ASPECTS IN THE TESTING OF TURBOSHAFT ENGINES

The needs with regard to equipment and changed test procedures will be determined by two main aspects:

Firstly, the development of modified or new engines and special applications:

- For example, to reduce heat and friction losses in helicopter engines, there will be an increasing tendency to omit the intermediate gear and include it in the rotor gear instead. This will mean higher braking speeds on the test stand.
- The performance of the engines will be tested under special simulated vibration conditions, because modern rotor systems will be more greatly affected by the drive.
- New control systems, for controlling the gas generator speed and for improved constancy of speed, will be introduced. These systems will provide modes such as:
  Primary control of shaft torque at constant speed with a simpler back-up control
  Engine overstress protection
  Transmission failure protection
  Power transient smoothing
- The stiffness of the engine suspension will have to be variable, to permit easier assessment of the dynamic characteristics of the engine and its behaviour under the service conditions in question. In addition, the intake and exhaust systems will be increasingly adapted to the conditions in the airframe.

Secondly, improved measuring and evaluation procedures:

- Improved instrumentation and test equipment
- More advanced computer-aided methods of diagnosis and fault analysis, calling for closer cooperation with the operator, to allow the test procedure to be better adapted to the engine application in question

In other words, tests for verifying the operability and durability of the engine will gain in significance.

Most engine overhaulers differentiate between

- Complete overhaul and test on the test stand, and
- On-condition maintenance with correspondingly limited testing

A number of operators are convinced that the latter alternative will become more and more important. However, this will necessitate great expenditure on reliable monitoring systems in the aircraft.

I am of the opinion that the trend will rather be toward scheduled preventive maintenance, since - in the final analysis and with regard to preventing life consumption - on the whole it represents the most economic method.

6. CONCLUSIONS

Although proof of an engine's performance is finally possible only in flight testing, I think sea level test facilities will grow in importance.

The testing of engines serves for demonstrating that technical objectives have been attained and that "diagnosis" and "therapy" have been applied properly. Testing merely for the sake of it is unprofitable and irrational.

The aim of the test engineer is to prevent damage by testing. For this he requires the appropriate know-how, aided by the equipment to permit him to recognize problems.

Finally when the engine is functioning properly, the test engineer wants to be able to appreciate why.

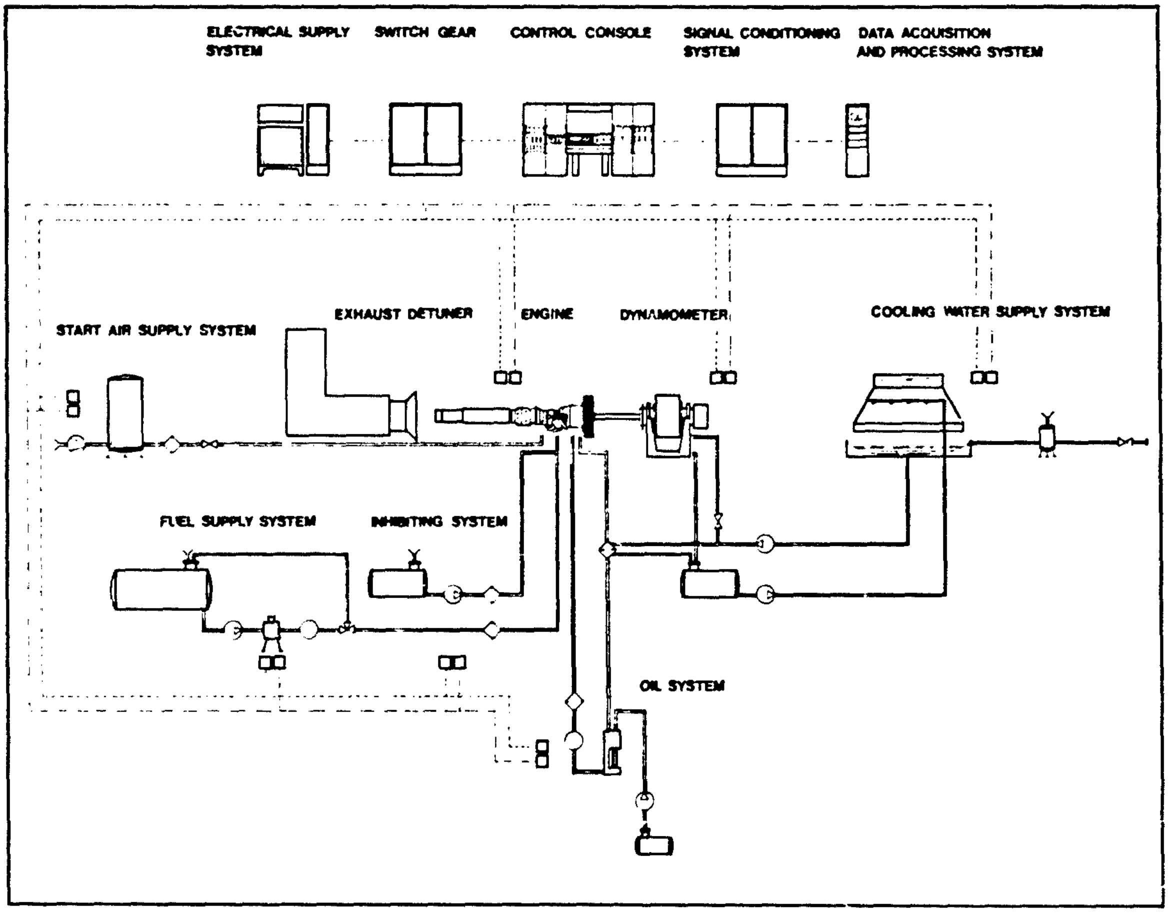


Fig. 2 Typical layout of shaftengine test facility

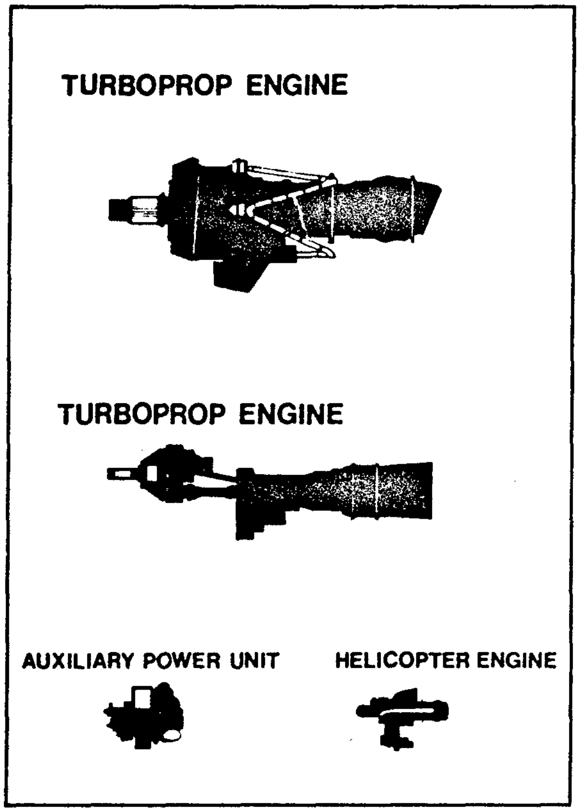


Fig. 1 Shaftengines, typical design

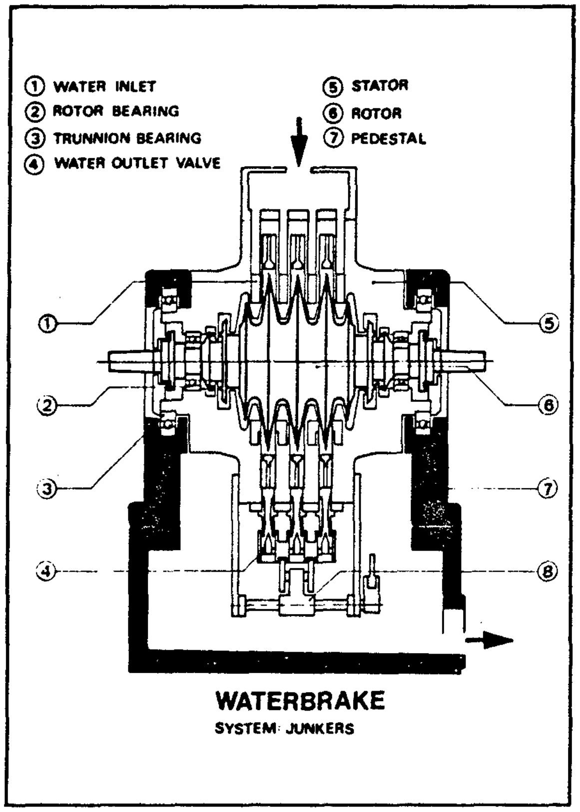


Fig. 3 Waterbrake

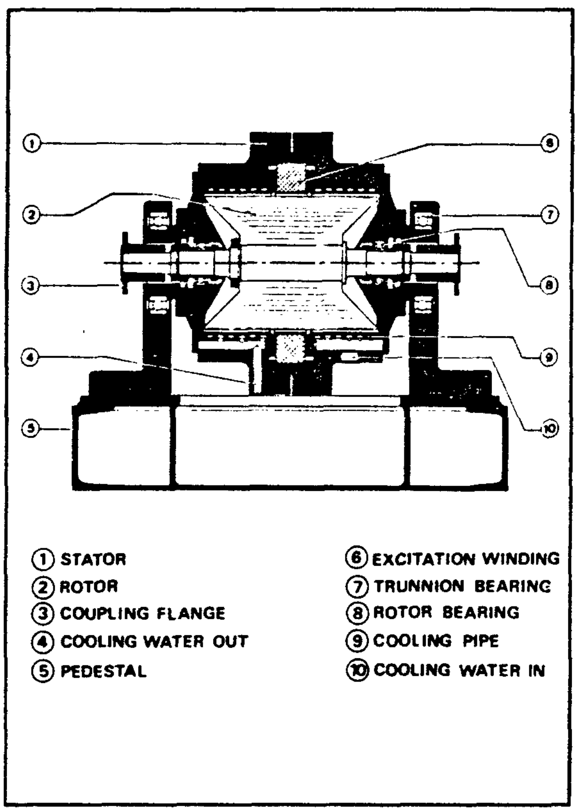


Fig. 4 Eddy-current dynamometer

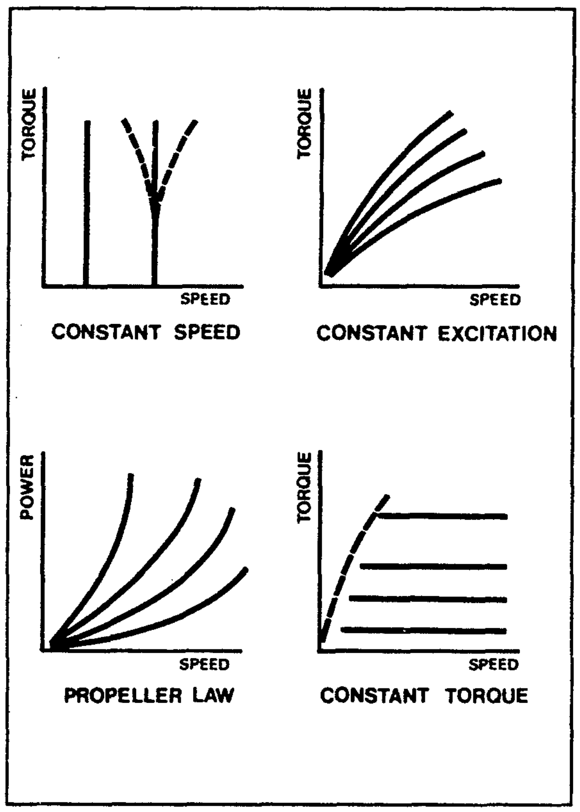


Fig. 5 Dynamometer,
torque/speed characteristics

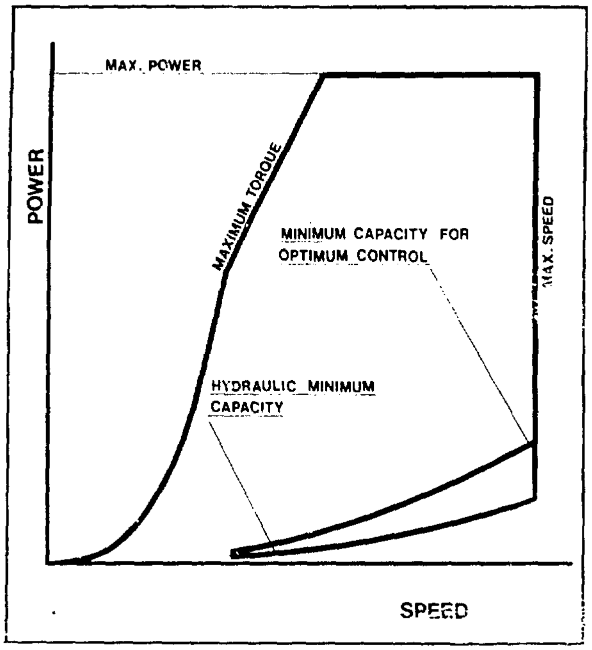
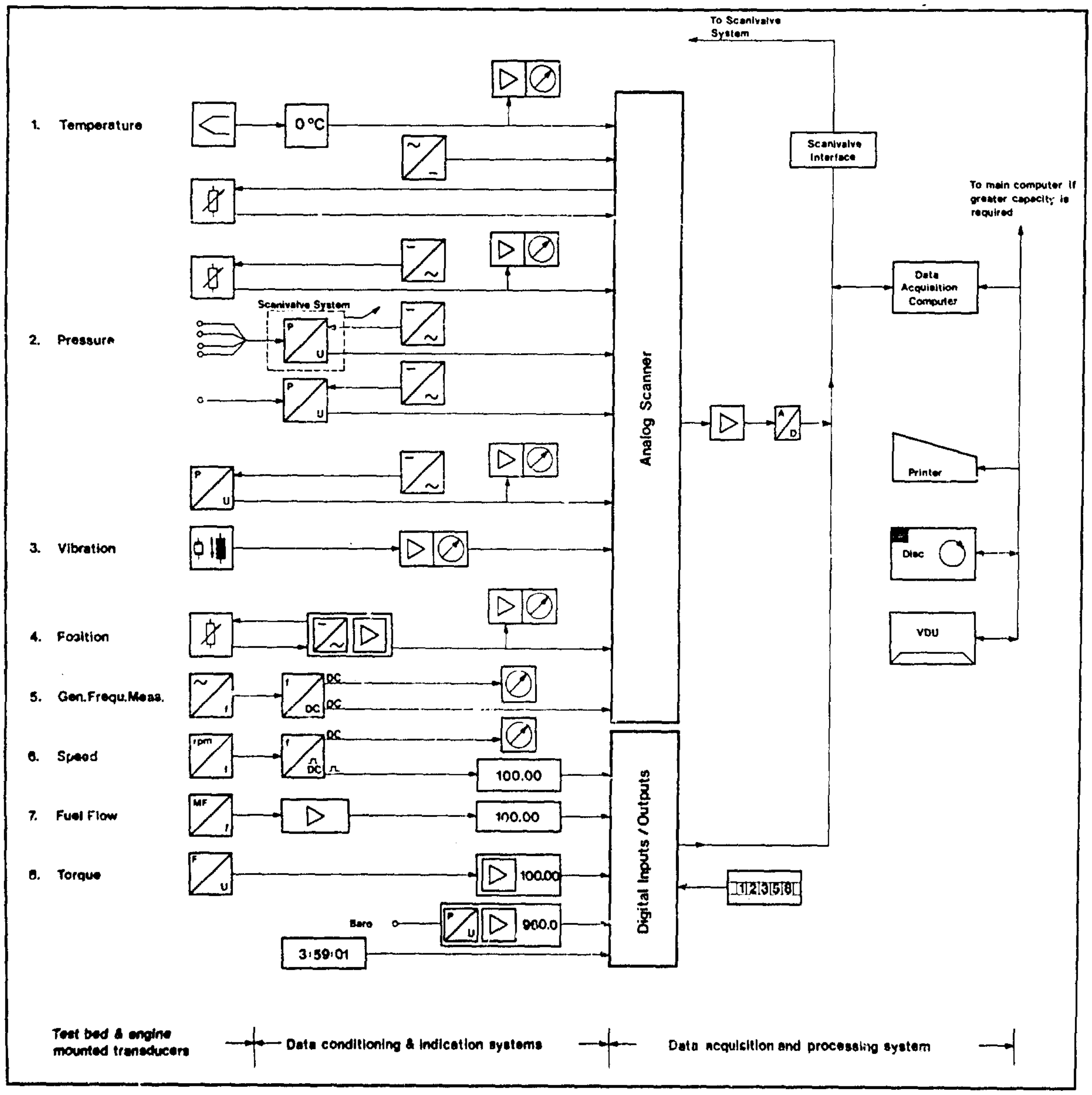


Fig. 6 Dynamometer, operating range

Fig. 7 Static measuring equipment for engine test facility



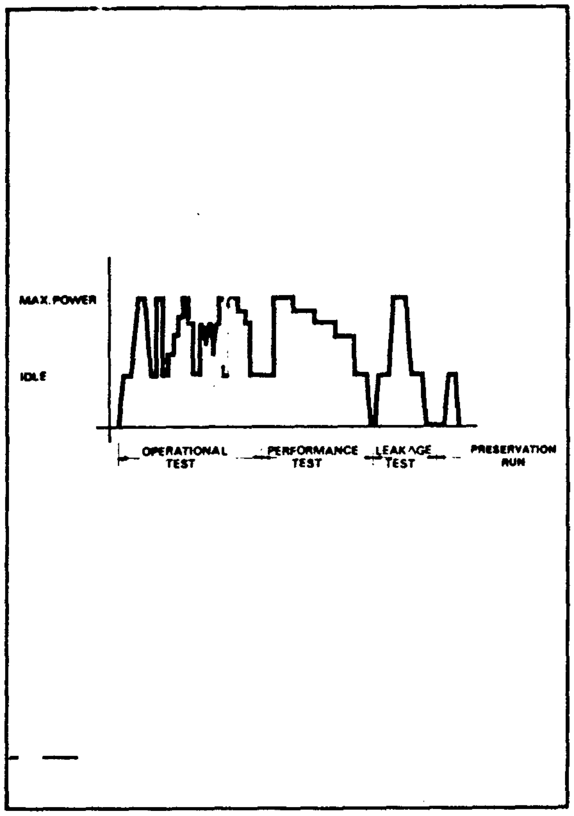


Fig. 8 Typical acceptance test, schematic

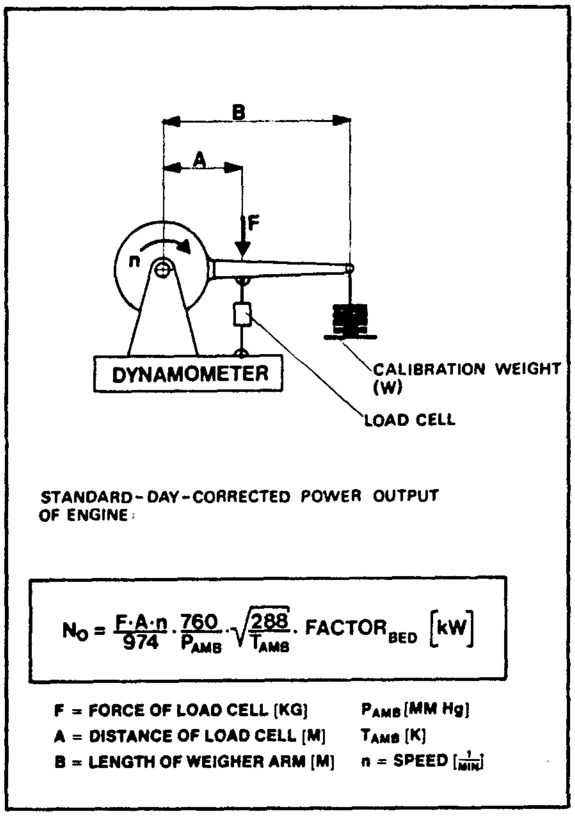


Fig. 9 Power output, standard-day-corrected

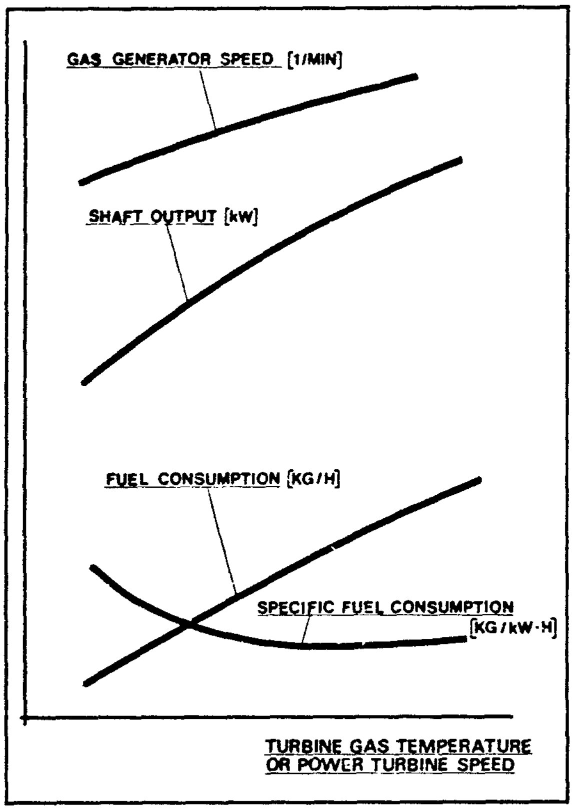


Fig. 10 Typical performance curves

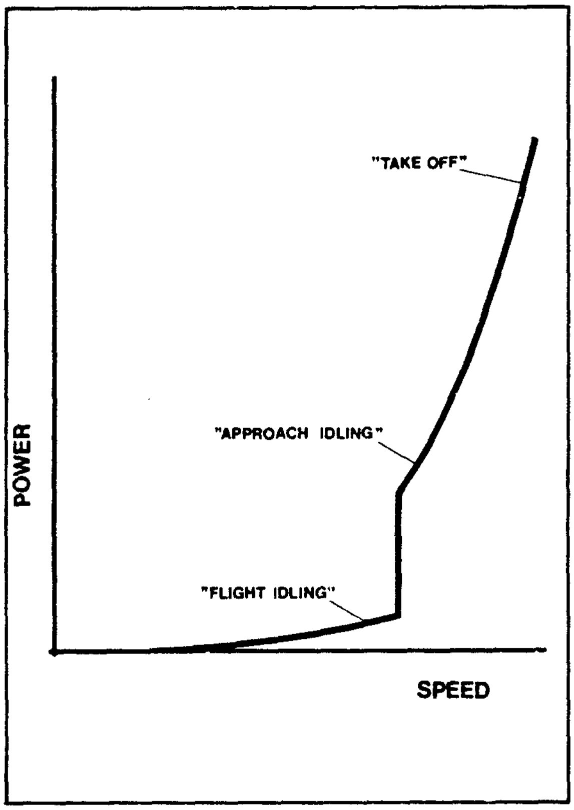


Fig. 11 Typical load/speed-interconnection curve

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DATA ACQUISITION AND PROCESSING IN SEA-LEVEL TEST BEDS

by

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1. INTRODUCTION

In the early years of engine evolution relatively simple low power engines could be tested on what now seem very basic test stands, needing only very elementary methods of measurement and data presentation. Engine technology has developed over the years and engines have grown in size and complexity bringing about spectacular gains in specific fuel consumption and power to weight ratio. In parallel has grown the need for more comprehensive testing and a demand for improved accuracy of measurement, increased numbers of measurements and more comprehensive displays of processed information. Advantage has thus been taken of equally significant developments in measurement and data processing technology, particularly in the field of electronics and microprocessors. The contrasting test beds in Figures 1 and 2 illustrate the point.

This lecture presents an overview of modern day data acquisition and information display in sea-level test beds, and to aid an understanding of the subject it has been conveniently divided into several sections, each of which covers a particular aspect of the overall process. Starting at the engine, or perhaps within it, a physical quantity such as pressure or temperature has to be converted into an analogue of its value and then transmitted to the control room where its value can be displayed to the test engineer as well as being recorded for later analysis. Thus the lecture first of all discusses the range of parameters that may need to be measured on a test engine and the nature of the signals which are output by the measuring devices. Next, the question of signal transmission is dealt with, and here the importance of preventing noise from degrading the transmitted signal is described. This is followed by a section on the important aspect of measurement calibration. Finally, the methods whereby signals are collected, stored and displayed are given some attention. In each section mention is made of the increasingly important role of microprocessors, particularly for data reduction, data analysis and monitoring of test data.

Before commencing with the technical content of the subject, however, a few words on the different types of sea-level test are appropriate because of the influence this may have on the selection and operation of data acquisition systems.

2. TYPES OF SEA-LEVEL TESTING

The primary objective of engine testing is to obtain information about the engine or its components, accessories or systems at defined operating conditions. At its simplest, this may be to demonstrate that an overhauled engine destined to re-enter service is airworthy and meets the minimum guaranteed performance. At the other extreme, a high performance military engine demonstrator, containing advanced technology components, may be comprehensively instrumented to enable component behaviour to be diagnosed and to allow close monitoring during a test to anticipate an engine failure. In between these extremes exists a whole range of test categories having varying objectives and complexity of test instrumentation. The following table assembled in a very approximate order of complexity, illustrates the point.

Type of Test	Objectives
Pass-off	Demonstrate performance guarantees and airworthiness after overhaul.
Endurance	Demonstrate capability of mechanical integrity and reliability over an extended period eg 150 hour type test or accelerated mission test.
Fault diagnosis	Identify reason for performance shortfall or component failure.
Ingestion	Demonstrate capability to withstand ingestion of foreign objects, sand or birds.
Systems development	Evaluate new technology systems or accessories, often on a well established engine, eg digital control system.
Engine development	Evaluate new technology engine components on an established engine, identifying performance benefits and any handling problems.
Demonstrator	Assess the overall performance and handling qualities of a completely new engine containing many advanced technology features.

The type of test will to some extent influence the accuracy of measurement required and to a much greater extent the rate at which data are gathered. For example, performance pass-off tests require high accuracy but only relatively slow response measurements whereas the evaluation of how a demonstrator engine fitted with a digital control system accelerates will demand a fast response measuring system. This subject will need to be returned to in a later Section after some of the technical aspects of data acquisition and presentation have been considered.

3. RANGE OF INSTRUMENTATION SIGNALS

There are many different physical quantities in a test engine which may need to be measured. The measuring device, or transducer as it is commonly called, should be designed for the particular quantity and gives output signals which are characteristic to its design and construction. Some of the more common measurement signals are discussed in the following section and a summary is given in the table below.

Quantity	Transducer type	Typical Signal Output
Pressure	a) Silicon bonded strain gauge	0 - 100 mV - depends on pressure range. Natural frequency 28 - 360 kHz.
	b) Vibrating cylinder	$\pm$4 to $\pm$ 11 Volts 20% deviation of centre frequency (44 kHz) for full scale.
Temperature	a) Thermocouple	0 - 54 mV (over 0 - 1350°C)dc.
	b) Resistance bulb	
Fuel flow	a) Turbine flowmeter	mV level pulse conditioned locally to voltage level square waves, 1 pulse per rev.
	b) Bulkmeter	Voltage level pulses conditioned locally to voltage level square waves. 100 pulses per rev.
Thrust	Strain gauged beam or diaphragm	0 - 30 mV for 15 Volts excitation
Rpm	a) Toothed wheel	20 mV per pulse (usually 60 pulses per rev) square wave output ($\pm$ 10V) after conditioning.
	b) Tacho-generator	3 phase output, rectified, squared and counted.
Vibration	a) Piezo-electric	Very high source impedance needing special signal conditioning to give output at dc voltage level (up to about 10 kHz).
	b) Strain gauge	Up to mV level output. Frequency normally dc to about 1 kHz.

3.1 Pressure

There are two main types of pressure transducer, as illustrated in Figure 3, which give an electrical output signal. The silicon bonded strain gauge type gives a low level dc output and the vibrating cylinder type has an output which varies in frequency with applied pressure. The strain gauge type gives a low level output, particularly in the lower pressure ranges, whereas the vibrating cylinder has the advantage of a much higher output signal but with a relatively high source impedance. The latter type is generally limited to pressures below 2 bar (absolute) and needs a built-in silicon diode to produce a compensating signal for temperature effects.

Both types of transducer can be used in a discrete manner, ie. one transducer per pressure tapping, but the strain gauge type also lends itself to a pressure multiplexing configuration in which many pressure ports in turn can be switched onto a single transducer, Figure 4. The transducer then has a flush diaphragm so that the entrapped volume of gas is kept to a minimum, thus reducing gas volume transfer and assisting response times. Although the transducer itself needs to have a fast response, when allowance is made for gas volume transfer and pressure settling times it may take up to several seconds to measure up to the typical number of 48 input pressures. It is thus mainly suitable for steady state testing, ie. taking stabilised performance measurements. A great advantage in its use for such work is that any of the input ports can be connected to a reference source and thus the system is self-calibrated on every scan.

3.2 Temperature

Temperature can be measured by two main types of sensor, thermocouples and resistance bulbs. Thermocouples have low internal resistance (about 10 ohms) and produce a steady dc potential of about 40 microvolts per °C (Chromel/Alumel). They have very good electrical properties and can adequately drive

100 metres of transmission line. At elevated temperatures (Max approximately 1350°C) they produce about 50 mV, but the relationship between temperature and potential output is not linear and for accurate work this should be taken into account. The rate-of-change of signal output is a function of the thermal time-constant of the junction and ranges from seconds to tens of seconds depending upon the temperature excursion.

Resistance bulb signals are produced from the change of ohmic resistance of a fine wire with temperature. The resistance change is very small and manufacturers supply conditioning modules complete with linearising circuits which give voltage level outputs. Like thermocouples, the signal outputs change at very slow rates due to the time taken to heat (or cool) the resistance bulb. Resistance bulbs are generally manufactured to two ohmic values, 100 ohms and 130 ohms.

3.3 Fuel-flow

There are two basic types of fuel flow measurement, one known as a turbine flowmeter has a miniature turbine suspended in a tube through which fuel flows, the other is referred to as a bulk-meter and has a positive displacement impeller which is rotated in proportion to the flow rate. Both are shown in Figure 5. Signals produced by the turbine-type flowmeter are generated as each blade passes a magnetic transducer, thus giving 1 pulse per blade revolution at mV level. Local signal conditioning amplifies and squares each pulse to give a constant voltage amplitude signal.

Bulk-meter signals are derived from a photo-transistor encoder attached to the bulk-meter shaft, the encoder giving 100 voltage level pulses for each revolution of the shaft. These are then conditioned in the same manner as the flowmeter although, owing to the normal calibration technique for bulk-meters in which the fuel passed in one complete revolution is accurately determined, it is usual to measure the time taken for 100 pulses as a measure of flow.

3.4 Thrust

Most modern load cells use some form of strain gauged beam or diaphragm which gives an electrical output proportional to the applied load. Such a device is shown in Figure 6. Electrical circuits provide excitation voltages to the strain gauge in the range from 10 - 15 volts and the strain gauges used are typically of 350 ohms resistance. At maximum load the signal output is about 30 mV and signal conditioning equipment is usually provided by the load cell manufacturers. Electrical outputs can be specified in either a digital or analogue format.

3.5 RPM

Two types of rpm transducers, the toothed wheel and tacho-generator are commonly available. The former is to be preferred because of its inherent simplicity and low cost and produces a pulse of about 20 mV amplitude each time a gear tooth passes the transducer (commonly, 60 teeth per wheel). Because the amplitude of the induced emf is proportional to the rate of change of magnetic flux, the pulse amplitude falls at low speeds. Signal conditioning is required in the form of amplification and pulse squaring, giving an output in the form of square waves of ± 10 volts amplitude.

The tacho-generator produces a 3 phase output voltage which is rectified, squared and counted in a signal-conditioning pulse counting unit.

3.6 Vibration

Vibration transducers fall predominantly into two categories, Piezo-electric types and strain gauge types. Piezo-electric transducers give signals from a source of extremely high impedance and require charge amplifiers to interface, buffer and amplify the transducer signals. Manufacturers of the Piezo transducer usually provide impedance matching and signal conditioning units which give voltage level amplitude signals and frequencies in excess of 10 kHz.

Strain gauge signals are of mV amplitude and an order lower in frequency response. Source resistance is approximately 350 ohms and voltage energisation and signal conditioning are required.

4. DATA TRANSMISSION

An engine running on a sea-level test bed presents an extremely harsh environment to the measurement transducers and instrumentation which contain either electronic components or delicate mechanisms. Although modern transducers and semi-conductor instrumentation can and do operate in difficult environmental conditions, to perform at their best an ideal environment of constant temperature, low humidity, negligible electrical noise and interference, stable mains supply, adequate access and above all freedom from vibration, is required. It is therefore desirable that, wherever possible, environmentally sensitive equipment should be moved to an adjacent site where these conditions can be fulfilled. If this preferred course is taken, data in the form of electrical signals has to flow along transmission lines connecting the test bed to the environmentally sensitive equipment in what is normally called the instrument room.

Degradation of the transmitted data, as shown in Figure 7, should be avoided at all costs. Most electrical signals will be in an analogue form and with degradation increasing with length of transmission it is desirable to locate the instrument room as close as possible to the test bed. In practice, however, because of other constraints it is not unusual to find the instrument room sited some considerable distance from the test bed and the transducer lines longer than desired. Unfortunately low level analogue signals are subject to other degrading influences, such as system noise and interference between adjacent lines. The signal levels range between microvolts (μV) and a few millivolts (mV), the former close to or even below self generated system noise and the latter still in need of significant amplification.

Notwithstanding these problems, low level analogue data transmission to the signal conditioning equipment in the instrument room is preferred to amplification at the transmitting end. Here, greater facility is offered for the filtering of electrical noise or unwanted signals, amplification of low level signals, conversion to digital formats and checking and calibration with known and traceable standards. All of this can be achieved in an environment which permits access to replace unserviceable or suspect equipment without the need to suspend testing. Some aspects of data transmission are now dealt with in more detail.

4.1 Low level Analogue Signals

The transmission characteristics and hence the cable specification will depend upon the technical specification of the transducers, thermocouples etc and the signal conditioning electronics. Most sea-level test bed data acquisition systems use PVC sheathed and screened twin conductor cable feeding into high quality differential data amplifiers. Transducers requiring electrical energisation and sensing of energisation voltage will use the same type of cable throughout. The low level cables are bundled together and run well away from other cables, especially those carrying high value alternating voltages or large current transients. The metal braided screens of the signal cables should be insulated so that leakage currents at points of contact along the test bed structure cannot create interference potentials which couple with the inner signal conductors. Cable screens are normally earthed only at the 'guard' terminal of the amplifier and with only one connection, cable screen leakage currents are reduced to negligible proportions.

Sea-level test beds are notorious for radiating a wide range of electrical interference signals from plant fuel and hydraulic systems, power cables, engine power supplies, slave electrical loading and electrical control and power actuators. All contribute to make the test bed a matrix of undesirable leakage currents which create alien potentials and which will, if permitted, degrade the low level measurement signals.

Another potential hazard to the low level signal is that introduced by the junction box. Ideally, the transmission line connecting the transducer to the signal conditioning equipment in the instrument room should be in one unbroken length, but owing to engineering and cost constraints line lengths are often broken down and require three or four connections. The junction box, or the connections within, can be the source of many communication and signal degradation faults owing to ingress of water, kerosene and hydraulic fluid. They are subject to thermal gradients and thermal EMF's and are available for all forms of manual abuse, such as being used as access steps on the test bed. As a result, broken conductors, discontinuous screens, short-circuits and leakage paths caused by moisture are only some of the more common problems arising in this area. Junction boxes should be carefully engineered to be water tight, or at least damp-proof, and to give effective electrical screening. Above all, adequate protection from manual abuse at the points of entry and exit of the transmission lines must be given and they should be placed away from main thoroughfares and access routes. False economy is not recommended and connectors used within the box should be of the highest quality giving high integrity joints and freedom from thermo-electric EMF's.

4.2 Line lengths

Problems may arise when transmission line lengths become significant (>100M) and frequencies start to rise (>10 kHz). With steady signals (dc) the concern is with the conductor resistance as well as capacitance and inductance formed between the two signal conductors and the screen. The longer the transmission line the greater these effects which load the signal and, in the steady-state case, reduce its amplitude. This may not be too serious for the signal conditioning stages as later amplification can make good the loss. With high frequency or transient signals, capacitive and inductive effects combine and produce more significant loading and, worse still, distortion of any fast rising or falling potentials. Fortunately, sea-level bed testing does not often extend into this régime, but if measurement above 10 kHz and greater than 100 metres transmission length are likely to be involved, there may be a case for signal conditioning closer to the transducer.

4.3 Digital data transmission

The transmission of digital data on sea-level test beds presents less technical problems than the transmission of analogue data. Digital data transmission is effected by conveying along the line a series of dc levels or pulses which have reasonably generous amplitude tolerance levels eg logic '0' is represented by -5 Volts ± 1 Volt and logic '1' is represented by +5 Volts ± 1 Volt. Data corruption or data loss can only occur when stray dc levels are present or when the desired logic levels extend beyond the tolerance threshold. In-built system checks in digital data transmission systems detect fault conditions and make an appropriate indication. High speed digital data transmission may present problems, especially over long distances, but these speeds (MHz) are not usually encountered on the sea-level test bed. Digital data transmission has the obvious advantage of high quality transmission but it does have the disadvantage that amplification, encoding and subsequent decoding have to take place before the original analogue signal can be retrieved, requiring additional equipment.

5. SIGNAL CONDITIONING

Signal conditioning covers a wide range of operations which may be performed in order to improve a signal or change its existing form into another one for the purpose of electrical compatibility. Figure 8 shows a typical group of signal conditioning equipment. The need for measurement accuracy is always in mind with high gain stability, good linearity, low intrinsic electrical noise, negligible zero shift, stable dc performance, high common-mode noise rejection and reliable and predictable long term operation being some of the factors to take into account. These requirements apply strictly to analogue signal conditioning, however, the conditioning of digital signals is considerably less demanding. Nevertheless, care must be taken here to preserve pulse shapes and amplitude thresholds which determine whether the level is a '1' or '0'.

With these requirements in mind the fundamental problem of electrical noise arises. Noise degrades measurement capability and its origin has to be known so that it can be reduced in effect.

5.1 Electrical Noise

The subject of electrical noise is complex and its coverage is restricted in this lecture to the two fundamental sources, thermal noise and semi-conductor noise.

Thermal noise exists in all electrical circuits and is primarily due to the random motion of electrons which increases with temperature. In practical terms, noise exists in any circuit containing resistance, including transducers, strain gauges, thermocouples, circuit wiring, transmission lines, etc. The noise energy generated is uniformly spread over the whole of the frequency spectrum and is related to absolute temperature thus:

$$E_{noise} = \sqrt{4kTR\Delta f}$$ where k = Boltzman's Constant
T = Temperature (K)
R = Resistance (ohms)
Δf = Frequency Band (Hz)

The two main components over which control can be exercised are resistance (R) and operating temperature (T), although the effect of the frequency component (Δf) can be reduced by filtering at the circuit point where maximum electrical noise occurs by either passive filtering (capacitors, inductors and resistances) or active filtering in the early stages of signal conditioning. The latter is usually preferred as the rate of cut off is more pronounced. All engine mounted transducers should thus have low resistance and operate at the lowest possible temperature. In some cases, when the measurement needs permit, transducers can be enclosed in a water cooled jacket to stabilise the temperature with short connections made to the parameter monitoring point.

Semi-conductor noise is due to the inherent nature of particle motion and to the random paths taken by individual charges. It differs from thermal noise in that the noise power per unit bandwidth varies inversely with frequency and is at its highest value at low frequencies. There is little that can be done to reduce semi-conductor noise at source. The latest high quality semi-conductors used in signal conditioning equipment generate relatively low levels of noise, but if these levels are still unacceptable the output can be filtered and the reduction in bandwidth will reduce the noise content. Care must be taken, however, to ensure that the full range of signal frequencies is not attenuated.

Electrical noise is generated at all points in the instrumentation system commencing at the transducer end and continuing along the transmission lines, its junction boxes and signal conditioning units up to the point where the data is recorded, displayed or converted into a digital form. At the point of digitization no further noise degradation should take place owing to the fundamental nature of the encoded signal. If the signal is reconstituted to an analogue form, noise degradation will again commence.

The sum of the noise levels will be of considerable interest for this will be a measure of the imperfections of the whole system. The theory of electrical noise summation depends upon many factors but to gain an approximate indication of the total noise present the root mean-square value of all noise present in the circuit of interest should yield a meaningful if not precise figure

Some practical forms of signal conditioning will now be considered.

5.2 Amplifiers

The amplification gain factor can be set by manual control for a wide range of input signal levels, or, if required, by programmable control allowing the amplifier to be automatically switched into a number of circuits requiring differing values of gain. Gain factor must be precise and stable and extend linearly through the full amplitude and frequency range. Internal noise of the amplifier should be as low as possible. Acceptable noise values for a dc data amplifier are $<10\mu V$ peak to peak, referred to input, and 1mV peak to peak referred to output. Electrical filtering may be desirable (filtering within the active stages of the amplifier leads to sharper cut-off points and greater rejection of unwanted signals) particularly when amplifying very low level signals where only a small proportion of the signal frequency is required. Variable filters permit the selection or rejection of a range of specific frequencies. Amplifiers which extend to dc levels must have good linear transition through the zero point, and dc offsets should be kept to a minimum.

Signal overload recovery must be rapid and the amplifier able to withstand output short circuit for an unlimited period. Zero drift with temperature change should be minimal. High common-mode-rejection is an essential feature of any data amplifier, this being the ability to reject any unwanted noise or interference signal appearing simultaneously at the input terminals of the amplifier. A typical figure is about 100 decibels over the frequency range dc to 100 kHz.

5.3 Multiplexers and Scanners

These units perform the function of sequentially switching many channels of low level signal data into expensive and hence shared conditioning equipment. High switching speeds and low signal degradation (analogue switching) are extremely important. Rapid switching permits more channels to be multiplexed and this reduces equipment costs and speeds up scanning rates. Analogue switching is more demanding than digital switching and requires careful engineering. Low level analogue switching should have zero forward and infinite backward resistance with minimal risk of noise or interference injection. Digital switching levels will tolerate finite forward resistance and less than infinite backward resistance together with a

reasonable degree of noise and interference injection. Mechanical switches are still used in low level analogue circuits but semi-conductor switches must be used for digital and high level analogue circuits. Semi-conductor switches continue to improve in switching characteristics and have the enormous advantage of high operating speed.

5.4 Analogue to Digital Convertors (ADC's)

This is a process of key importance in any data acquisition system; high conversion accuracy and speed are essential requirements. Currently, analogue data can be multiplexed onto an analogue-to-digital converter and converted at the rate of 250 kHz. It is anticipated that these rates will eventually reach MHz proportions and when this is possible the unit cost per channel for hardware will fall considerably.

5.5 Transducer energisation (dc)

Most pressure transducers in use on sea-level test beds are of the silicon bonded strain gauge type and have a Wheatstone Bridge circuit in which two arms are active strain gauges and two passive. Electrical energisation is required and this is derived from a stabilised dc power supply (usually 5 - 10 Volts output). Changes in temperature, lead resistance, transducer loading etc, can cause the set value of the energising voltage at the transducer terminals to change and a voltage-sensing signal is fed back to the transducer power supply which indicates the discrepancy and makes a correction.

5.6 Filters - passive and active

Electronic filters are designed to accept or reject specific frequencies and, provided the basic data signal is not altered, its quality can often be improved by filtering as illustrated in Figure 7. Simple filtering of the passive type can take the form of capacitive, inductive, and resistive components wired into a band-pass or band-stop configuration. However, signal amplitude losses and changing phase relationships can be introduced by filtering so careful design is essential. More effective active filtering, giving greater attenuation, sharper frequency cut-off, etc can be achieved by incorporating a filter in the feedback circuits of an amplifier. However, this can be a complex design problem area and is best left to an expert in this field. Commercial amplifiers with filters having a wide range of frequency characteristics are currently available.

5.6 Interfaces

An interface permits effective coupling or communication between two (or more) electrically incompatible units. For example, an electronic unit may have a high output impedance and have to feed its signal into another unit with low input impedance; the second unit would load the first and the link would fail. An interface in the form of an impedance changer can be introduced so that both units see their ideal impedance. Not all examples are as simple as this, but the principle remains the same. The need for interfacing occurs in both analogue and digital hardware circuits and also in software.

6. CALIBRATION

Regular calibration of the data acquisition system is essential if confidence is to be maintained in its accuracy and to avoid the collection of faulty data. Some instruments have to be removed from the test bed and calibrated in a separate laboratory, whilst others are best calibrated in situ. Thus it will be seen from the following examples that calibration methods need matching to the quantity concerned with the only common factor being careful attention to detail.

6.1 Fuel Flowmeters

Flowmeters used on sea-level beds (turbine type for lower flow rates and bulkmeters for higher rates) need regular calibration for which purpose they generally require removal to a calibration rig. Such a rig can be quite complicated as illustrated in Figure 9. Here, precision weighed quantities of a known fuel whose temperature, pressure and density are accurately monitored are passed thorugh the flowmeter and timed at rates which cover the range of the instrument concerned. Flow rates are computed with a tolerance that should be better than 0.1% of the true flow. Flowrates on the test bed can vary over a range of 10:1 and accuracies should approach 0.15% over the range. Flowmeter outputs are usually encoded into electrical pulse trains which are proportional to flow rate so these can be readily simulated by electronic means and injected electrically at the flowmeter to check the electronic transmission, display and recording system.

6.2 Load Cells

The accurate measurement of thrust is not only one of the most important but one of the most difficult to achieve in the entire range of test bed parameter measurements. Particular care must be taken to ensure that the test bed is free to move, being resisted only by the load cell itself. Thus great attention to detail is necessary in running instrumentation lines from fixed points surrounding the engine to the measuring point so that these do not restrain the test bed's movement, preferably being laid out at right angles to the thrust axis. All of the instrumentation, load cell(s), signal energisation and monitoring lines should be calibrated in-situ against a transfer-standard load cell sharing the same mechanical and electrical environment as the thrust measuring load cell. The calibration programme must follow as closely as possible the loadings and environmental conditions to which the system is exposed during normal testing. The transfer-standard load cell, together with the instrumentation simulated signal lines, etc, should be removed for testing at regular intervals and itself calibrated against an appropriate National Standard.

6.3 Thermocouples and resistance bulbs

These devices are usually calibrated by substitution methods mainly because it is impractical to subject them to a wide range of precisely known temperatures, mostly elevated, whilst situated on the test bed. Thermocouples are manufactured from high purity metals which are subject to stringent quality control and once the couple has been fused the measurement accuracy is taken as that stated by the manufacturer of the metal. For a typical Chromel-Alumel junction the quoted accuracy is ± 3°C in the range 0 to 1400°C. If independent calibration is essential a 'fluidised' bed of sand, commercially available, will give temperature uniformity within ± 1°C over the range ambient to 650°C.

Signal circuits into which the thermocouple EMF's are fed can be checked by injecting electrical potentials equivalent to the range of the appropriate thermocouple output. Traceable precision voltage sources substituting for thermocouple EMF's enable temperature channels to be traced to National Standards.

The thermocouple reference junction plays an important part in establishing measurement accuracy and, although dated and labour-intensive, ice-reference flasks are still significantly more accurate than electrically generated thermal reference points, although they do suffer from the disadvantage that in prolonged sub-zero ambient temperatures errors can be injected at the ice reference point.

The calibration of resistance bulbs is similar in principle to that of thermocouples, with traceable values of precision resistance being substituted for the resistance bulbs. Resistance thermometers are on average an order better in measurement accuracy than thermocouples; the latter can be improved by polynomial curve fitting to selected thermocouple channels which enhances measurement accuracy to the standards of the former.

6.4 Pressure Transducers

Calibration of the discrete pressure transducer is straightforward, providing access is obtainable to apply the calibrating pressure. A primary pressure standard, such as a commercially available dead weight tester, as illustrated in Figure 10, or quartz-bourdon pressure test set, which have accuracies at least 3 or 4 times better than the specified accuracy of the transducer undergoing calibration, is necessary to monitor the applied calibrating pressure. Batches of discrete pressure transducers can be connected by a manifold and calibrated together. Alternatively, a single transducer can be removed from the engine and calibrated in the laboratory.

Calibration of the transducer in a multiplexed system can follow along similar lines laid down for discrete transducers. However, the nature of the device permits the sequential scanning of the input pressure ports and giving some of these up to a reference pressure source allows automatic calibration of the measurement system once per scan.

7. DATA COLLECTION, DISPLAY AND STORAGE

Engine measurements having been successfully captured and transmitted to the control room must now be collected, displayed and stored. Parameters that the test engineer should observe need to be displayed with clarity to aid easy assimilation of data without being obtrusive or distracting. Displays should ideally enable readings to be quickly taken at stable conditions as well as indicating the rate of change of rapidly varying measurements and the approach to limiting values when corrective action needs to be taken. The layout of control rooms is thus a subject requiring careful attention to detail and a typical control panel is shown in Figure 11. Only a small proportion of the measurements taken, however, will need to be displayed, the majority being recorded for later analysis.

Although the emphasis in the earlier Sections has been on electronic based systems there is still a minor role for the non-electrical analogue system and these are included here for the sake of completeness. This Section first of all deals with the simple analogue presentation of measurements before turning to look at the more sophisticated electronic and computer controlled installations.

7.1 Analogue displays

Non-electrical instruments are unlikely ever to be completely eliminated from sea-level test beds although the long established mercury manometer is rapidly being phased out of most modern control rooms. Bourdon gauges and moving coil or moving iron type electrical meters may still have a useful role to play, having scales with a needle indicating a quantity such as pressure or temperature in absolute terms, or in percentage of full scale if preferred. These displays are mainly suitable for slowly changing parameters whereas the ultra-violet mirror galvanometer chart recorder is used for capturing fast moving measurements. Where the response is not so fast, but the trend of a changing quantity over a period of time needs to be established, the strip-chart recorder plays a valuable role.

7.2 Computer-based systems

Engine tests which generate a lot of data, particularly when engine transients are being investigated, have come to rely increasingly upon computer-based data gathering systems, typified by the one shown in Figure 12. These enable a lot of data to be gathered and processed in a short space of time, with only the essential parameters being displayed to the test engineer to aid his conduct of testing. Each measurement to be taken is identified by an address which is unique and identified by the computer. Where possible, transducers, thermocouples and other measuring devices are grouped together in similar types to

take advantage of common signal conditioning equipment eg 50 pressure transducers can share the same energising signal conditioning equipment. Similarly, 100 thermocouples can share the same amplifier. The computer can also control peripheral equipment such as line printers, graph plotters, storage media, etc and can contain a software library of engine test analysis programmes written to cover the broad range of testing envisaged. Once a program is loaded, the computer will respond to its software instructions and address the test parameters in a predetermined order. The analogue signal present on any selected address is digitized and transmitted back to the computer; the next parameter is then selected and digitized by the same process. When all parameters have been addressed and their data digitized, the scan, which may comprise many hundreds of parameters, is complete. An engine test point may be repetitively scanned and the data averaged. On-line computation may be performed and output, placed in store for further computation at a later date or for record purposes.

One of the advantages of the computer-based system is that once the program has been loaded and the scan initiated, no further manual intervention or action is necessary. The scan does take time however (about 60 to 80 addresses per second) and if, say, 600 parameters are being accessed, then 10 seconds or so will have elapsed between monitoring the first and last addresses. Note that multiplexed pressure measuring systems take about 12 seconds for their own pneumatic scan and this must be added to the computer scan time.

Data required during the test to aid the test engineer and his staff can be made available on visual display units, line printers etc, and assessments can be made within a very short time of the scan being completed. A selection of such equipment is shown in Figure 13. Data can also be transmitted over land lines to other engineers who would otherwise have to attend at the test site themselves.

7.3 Driving and monitoring displays

As few sea-level tests are totally under automatic control with remote supervision it is nearly always necessary to display some of the data in a form which can be interpreted by the Test Engineer, as shown in Figure 11. The best way to do this will be influenced by many factors, including the type of test, the importance of the reading, and the convenience and cost of providing certain display types. As a typical engine test on a sea-level bed may require a large number of measurements to be displayed, a lot of thought needs to be put into achieving a visually acceptable and efficient layout. During a test, the overriding responsibilities of the test engineer are likely to be safety of personnel and safety of engine and test plant. Once these aspects have been catered for, the next priority will be to achieve the test objectives at minimum cost in time and resources. In providing data displays to aid the task a design must be implemented which is a compromise between sufficient data to do the job and a cluttered layout, providing a balance between the need for safety monitoring displays and for meeting the test objectives. In practice, the nature of an engine test often results in there being considerably more data displays for health monitoring than for engine control. For example, under most circumstances a particular shaft speed will imply a particular value of jet pipe temperature, combustion chamber pressure, thrust and so on, whereas all of these will need to be separately monitored to provide reassurance that the engine is in good health.

A choice of the type of display will be influenced by, amongst other things, the need for an accurate or approximate display, the time typically available to read it, the number of people who require to view it simultaneously, the maximum rate-of-change of the value and whether an associated alarm is required. Display types fall into two broad categories, analogue and digital, each with its own advantages. Analogue displays, where the value of the measurement is represented by the position of a needle, pointer or similar indication, are very quick to read and often provide the best way of estimating proximity to alarm levels or rate-of-change of a value.

Modern digital equipment is nevertheless steadily replacing analogue indicators in applications where precision is important, although from an operational point of view the modern high resolution decimal read-out device lacks the facility, previously taken for granted with analogue displays, to see visually the rate-of-change of readings. The digital device tends to produce an unintelligible blur of figures until the reading settles down or is 'frozen'. It is interesting to note that some of the latest digital displays also incorporate a feature which shows rate of change on a peripheral analogue display and this type will probably gain popularity as its cost reduces.

An important step forward in display technology has recently been achieved in the form of computer generated simulated displays, which enable the best points of the different display types to be combined and which allow unprecedented flexibility. Using this system, illustrated in Figure 14, there is none of the usual display hardware as panels of dials and gauges are replaced by a single cathode ray tube display screen on which are displayed a particular set of simulated instruments using images generated by a small computer. Using this system the most appropriate subset of instruments can be selected and altered to suit the current phase of testing, alarm levels can be readily displayed and alarm states announced by use of colour information, and automatic switching can emphasise readings requiring attention. It is even possible using this latest generation technology to adjust the display during a run to suit particular circumstances, and with good software this can be done without loss of continuity of other important readouts.

7.4 Data processing

Once data have been collected from an engine under test they will usually undergo some further analysis. In a typical modern test facility a scientific or analytical computer may be connected directly to the data gathering equipment and this allows the data to be fed directly to the analysis programs and processed immediately. On the other hand the data may be fed instead to storage devices for later analysis 'off-line', after completion of the test.

Both approaches have their advantages as will now be discussed.

7.4.1 On-line processing

There are powerful reasons for favouring on-line processing, including what are probably its two most valuable aspects, the safety monitoring capacity it bestows and its feedback potential ie. the abilit to influence the conduct of the test. Figure 15 shows a display of performance parameters for monitoring purposes. The fact that the data are processed immediately after collection means that the calculated results can be studied and used to guide the course of the test and monitored to check for deterioration of engine performance which may be a prelude to failure of a component. With suitable modern processors and graphical displays, the analysed data may be presented in compact and understandable form so that deviations from an expected line on a computer generated graph may be easily shown up. Likewise, the point at which sufficient data have been gathered may be decided and the current phase of testing curtailed.

There are certain disadvantages that accompany this otherwise highly desirable procedure. The equipment used must be capable of handling the resulting work load and so a dedicated, fast and powerful computer must be available, which implies greater expense in both procurement and use. Similarly, the data made available by this sophisticated equipment must be studied by highly trained engineers if the significance of the information is to be appreciated. This tends to imply that the test must be of shorter duration, as full value will only be gleaned from the resulting data if they are continuously monitored by the same personnel. It is also probable that time between test points may be greater than engine and plant restraints would impose as delays are likely to be incurred while unexpected events are examined or courses of action decided.

This all results in a very high cost per test point and very high efficiency is therefore required if full on-line processing is to be employed to good effect.

7.4.2 Off-line processing

Normally, during off-line processing, the pressures imposed by running the engine are not present. There is no requirement to do the analysis in the shortest possible time and hence a deeper, more studied approach is possible. The intended test programme is planned in advance and the resulting test schedule followed for the duration of the running period. The data collected during testing are then analysed in a relatively quiet environment before planning the next stage of testing. A test of this nature can be run by test technicians and there is no requirement for specialist engineers to be present. Similarly, the data gathering can be done by a relatively cheap data-logger without sophisticated computational abilities. The computer used for post test analysis need not be particularly fast and may therefore be shared between different functions.

Although such an operation can mean relatively cheap testing, the obvious drawbacks are that the quality of the data cannot be ascertained until they are examined after completion of the test, and problems that arise during the test are more likely to lead to premature shutdown if engine performance experts and specialist engineers are not present to decide on alternatives to ending it.

Thus choice lies between expensive but potentially highly productive on-line testing and a cheaper alternative with a greater risk of wasted time and expense. For any particular testing situation it is important to make the right choice, and in most cases the optimum arrangement will be a compromise somewhere between the two extremes, with the proportion of each being influenced by the previously discussed factors.

8 DISCUSSION

The pace of engine development shows no signs of slackening as new engine designs or advanced versions of engines already in service emerge to meet the competitive pressures of both the airline and the military equipment market. As far as engine testing is concerned there would appear to be no slackening in the demand for sea-level test facilities although there will be changes in the way test facilities are used. The trend is inevitably towards greater efficiency and hence lower testing costs, with larger numbers of measurements being taken, more use of computer aided data reduction systems and the more widespread application of computer controlled display systems.

Pass-off testing and endurance work probably presents the greatest opportunity for automation of the complete process of data collection, processing and displays. Instrumentation can be common to a particular engine type and can be connected to the engine under test using snap-connectors. The test schedule could be preprogrammed in advance, the data collected, analysed and compared with the specified performance completely under computer control. Threshold limits could be set which, if exceeded, would only then demand a human operator to intervene.

As far as development work is concerned, there is perhaps less scope for complete automation here but nevertheless improvements are likely. Again, the trend is towards concentrating the manual activities that now demand experienced personnel to be present and which occupy thinking time before the next item on the test schedule is commenced. Thus for routine development work on a reasonably well established engine the computer controlled test schedule may also become the acceptable way of operation.

For the more exploratory type of development work, where the course of events can never be accurately predicted, manual control of tests and close surveillance by specialist engineers will remain necessary. Here, however, more measurements will need to be collected in a shorter space of time with particular emphasis on vibration monitoring and the analysis of engine transients.

Whatever the type of testing, the increasing cost and complexity of modern engines demands a corresponding increase in the accuracy and integrity of the measurement system. Small improvements in performance can mean a lot in terms of returns both in immediate cost savings and in longer term sales potential in a highly competitive market, but small improvements need very accurate and consistent data systems to reveal them. It is by exploiting the advances in electronics technology that data systems have achieved today's high standards and continued improvement seems to be attainable. Thus data acquisition, processing and display will remain one of the essential requirements of sea-level testing.

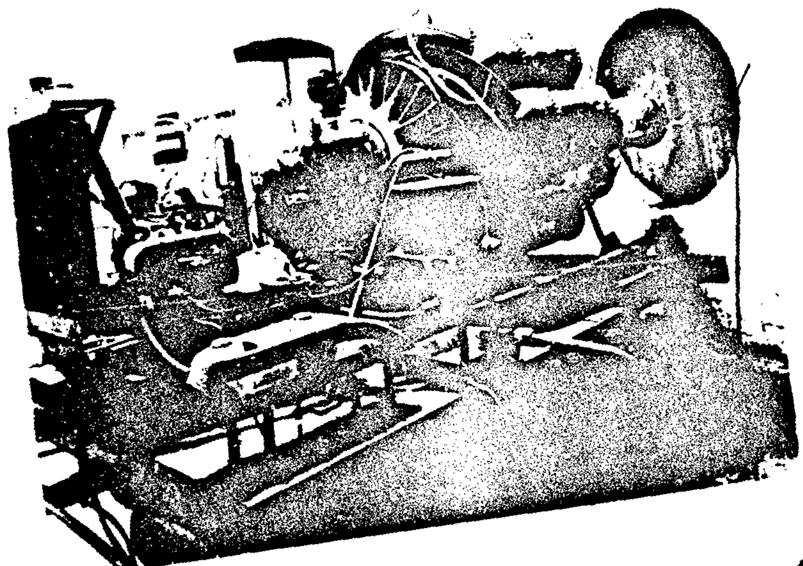


FIG 1 SEA-LEVEL TEST BED c 1939

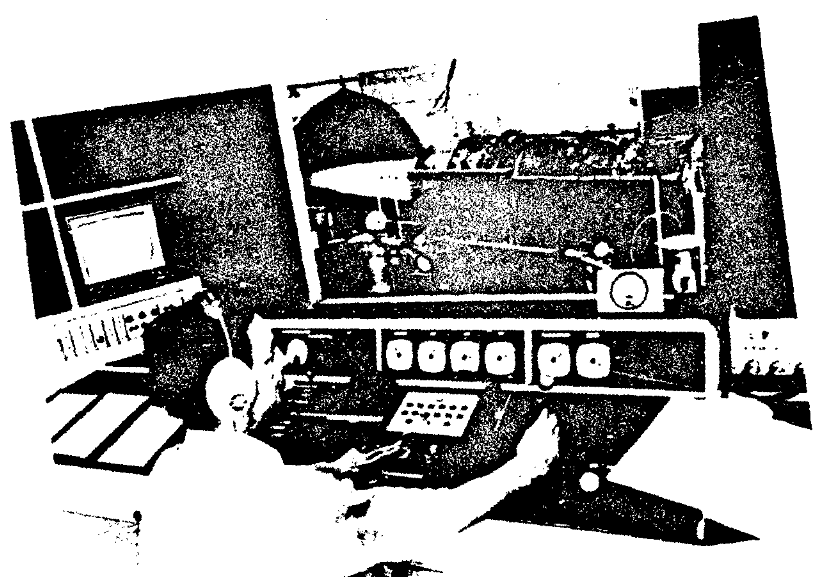
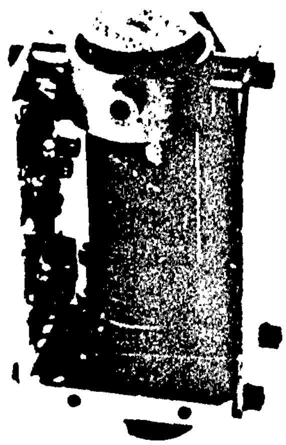


FIG 2 MODERN SEA-LEVEL TEST BED



(a) VIBRATING CYLINDER (b) STRAINGAUGE TYPE

FIG 3 PRESSURE TRANSDUCERS

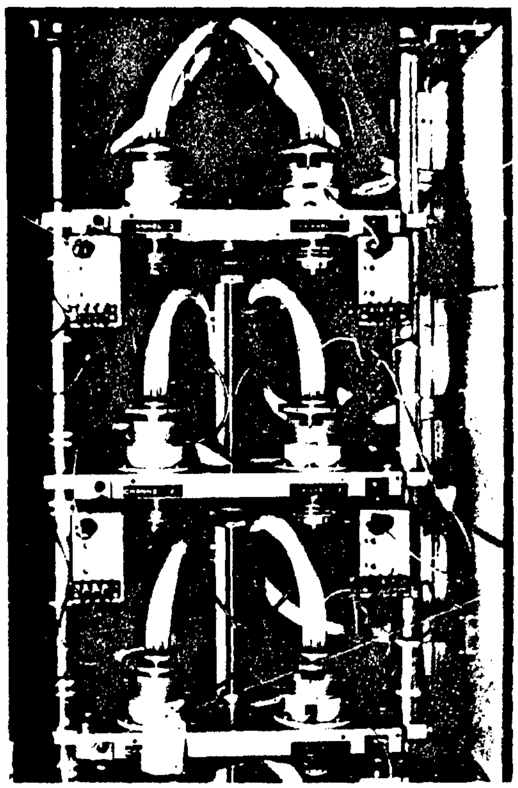
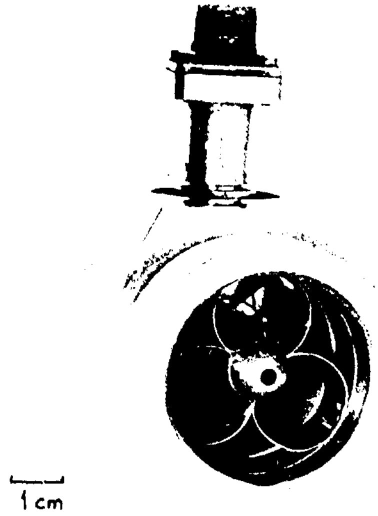
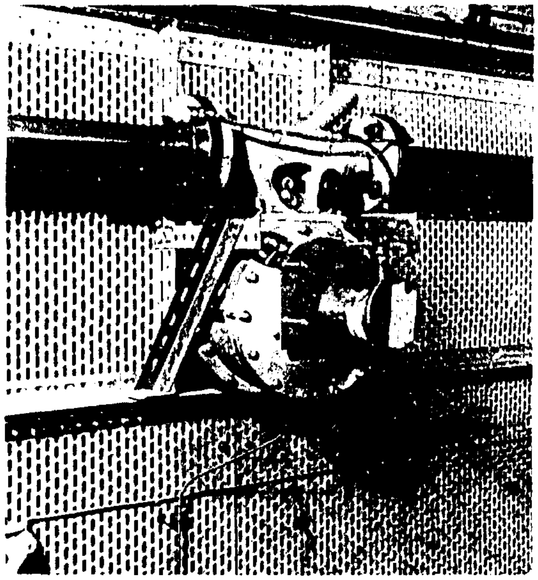


FIG 4 PRESSURE MULTIPLEXED TRANSDUCERS



TURBINE FLOWMETER



BULKMETER

FIG 5 FUEL FLOW MEASUREMENT DEVICES

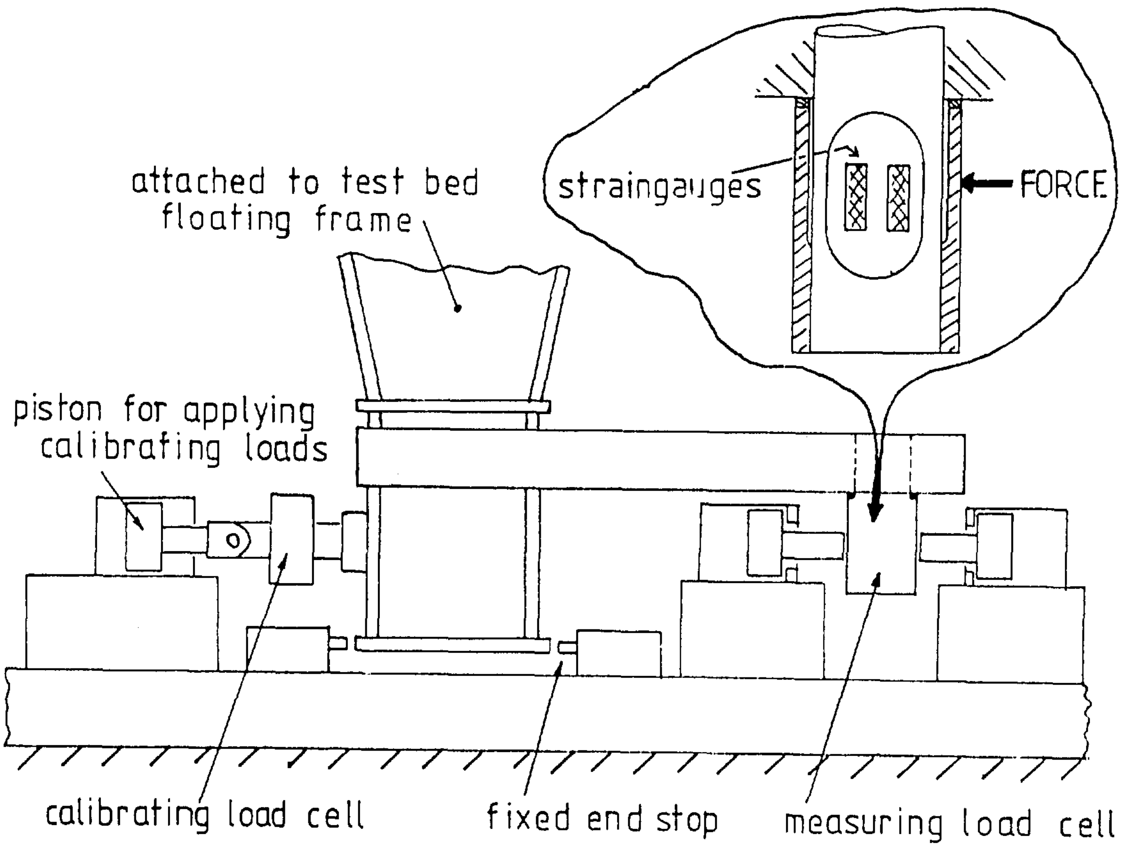


FIG 6 LOAD CELL FOR THRUST MEASUREMENT

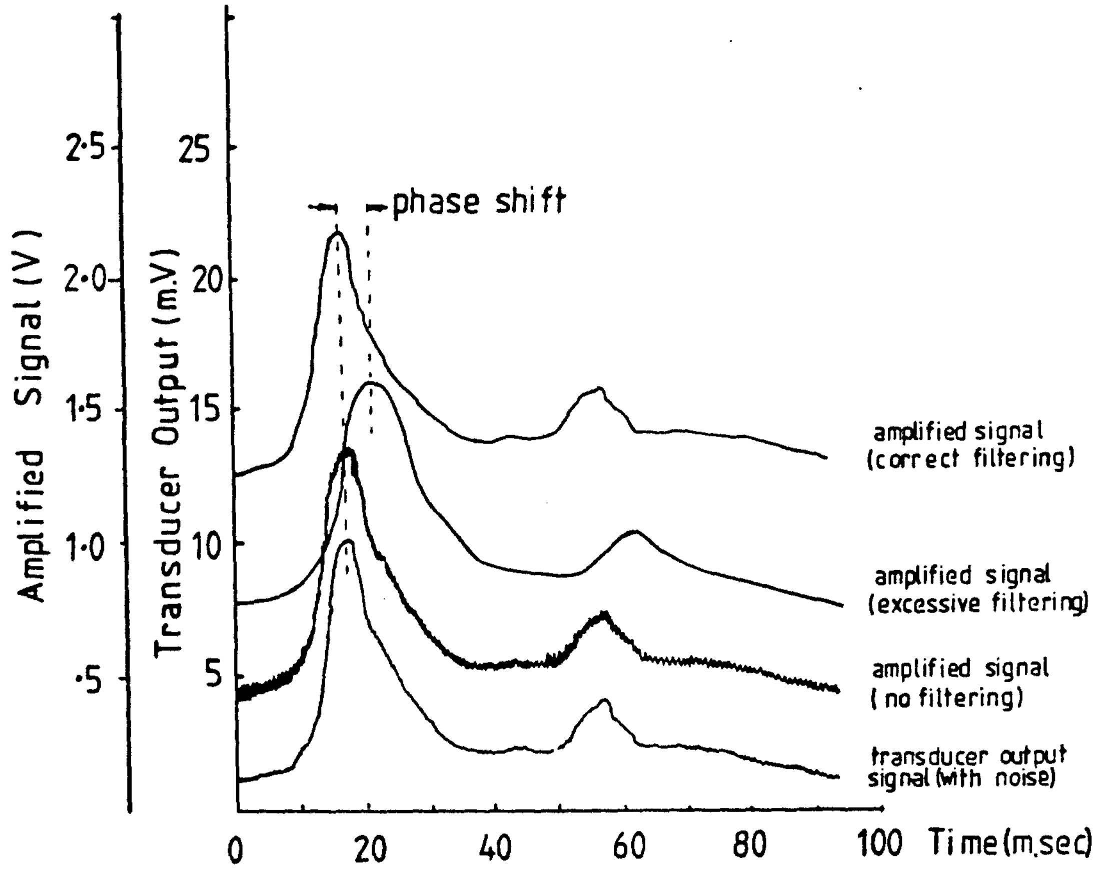


FIG 7 SIGNAL DEGRADATION & FILTERING

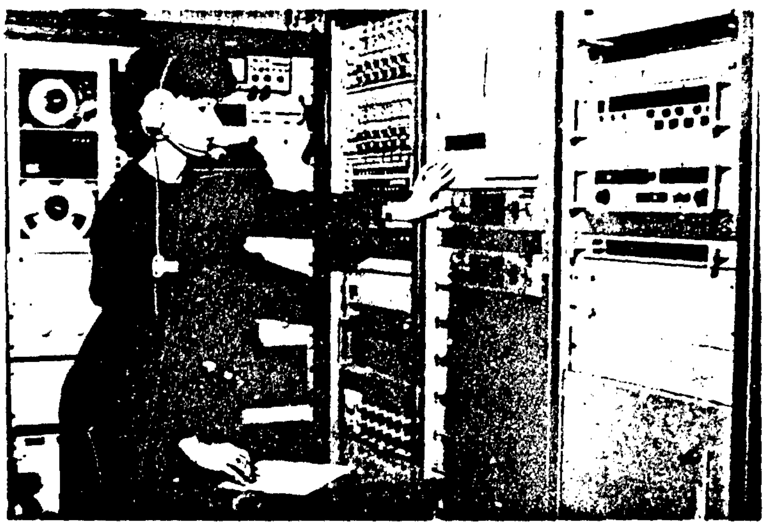


FIG 8 SIGNAL CONDITIONING EQUIPMENT

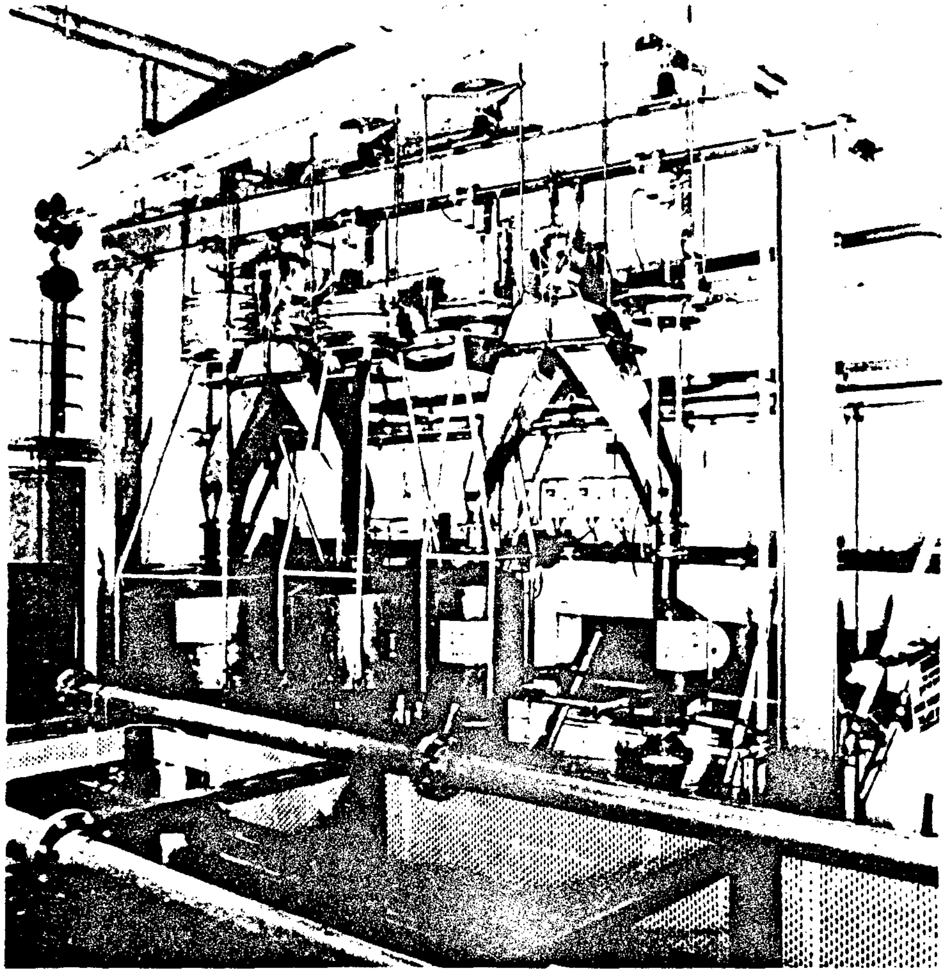


FIG 9 FUEL FLOW METER CALIBRATION RIG

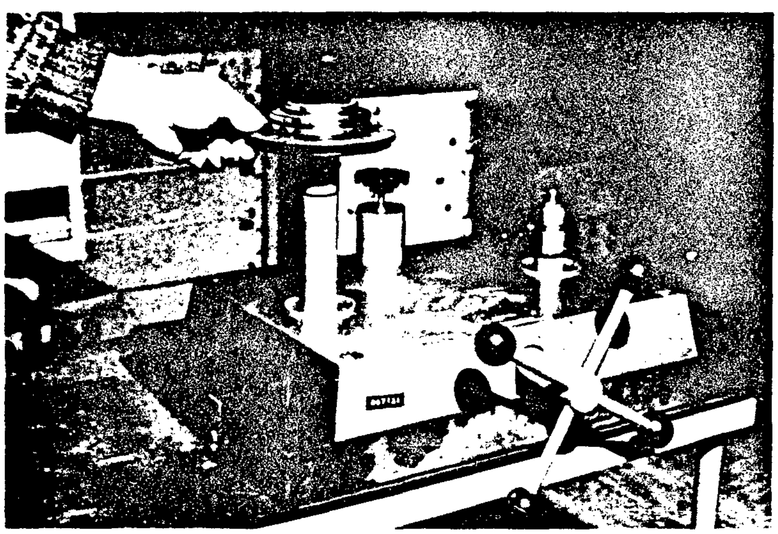


FIG 10 DEAD WEIGHT TESTER

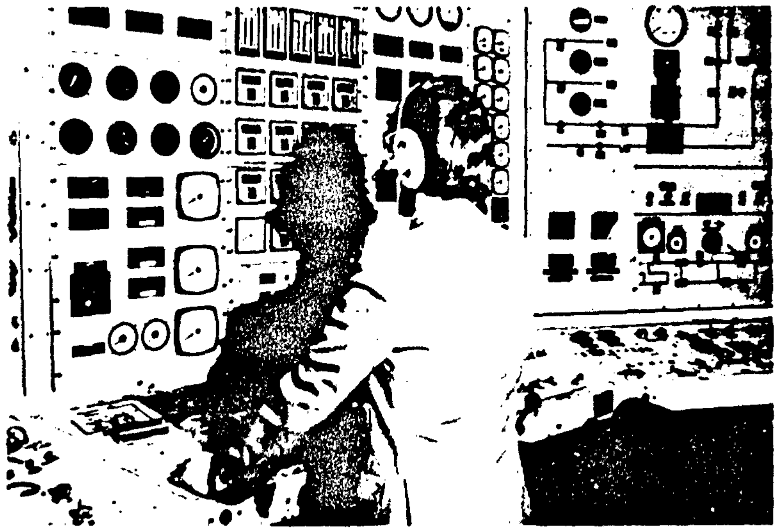


FIG 11 CONTROL ROOM DISPLAY PANEL

FIG 12 COMPUTER BASED DATA GATHERING SYSTEM

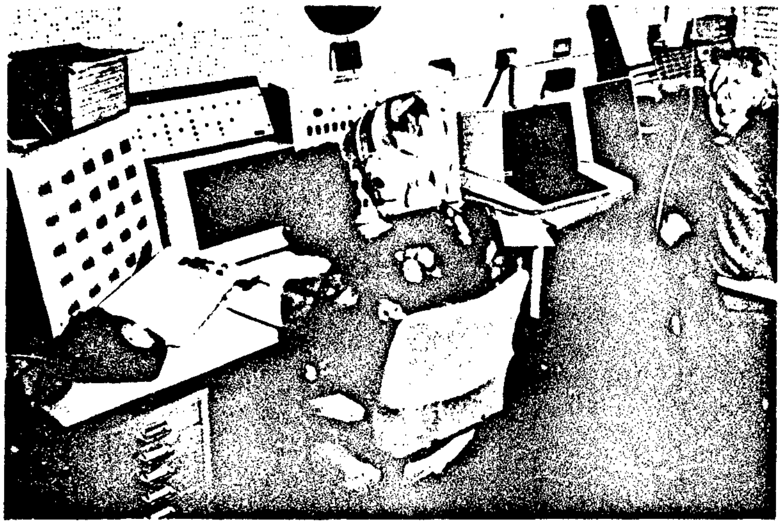
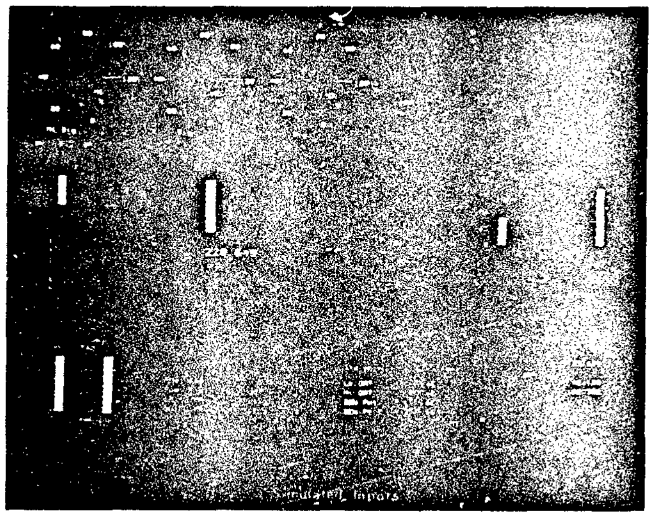


FIG 13
VISUAL DATA
ASSESSMENT
EQUIPMENT

FIG 14
COMPUTER GENERATED
INSTRUMENT DISPLAY
SYSTEM



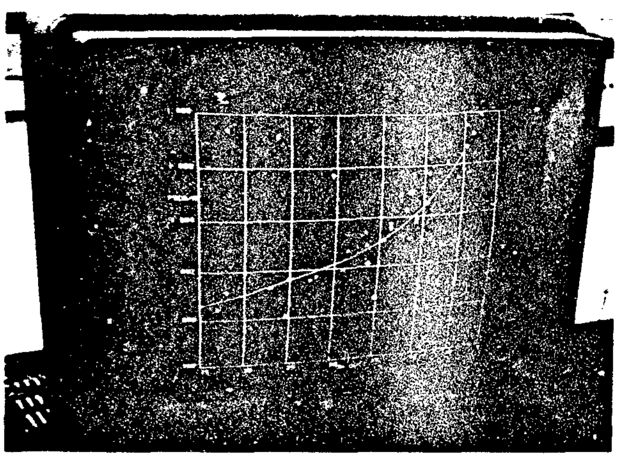


FIG 15
PERFORMANCE MONITORING
DISPLAY

UNINSTALLED AERO ENGINE TESTING IN OPERATION IN THE ROYAL AIR FORCE

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Flt Lt Pickavance and UETF Staff
RAF St Athan, S Wales

Chf Technician Read and UETF Staff
RAF Honnington, Suffolk

Chf Technician Hepworth and UETF Staff
RAF Coltishall, Norfolk

Chf Technician Walsh and UETF Staff
RAF Conningsby, Lincs

Credits to: The IAC Co
Staines, Middlesex

Marconi Avionics
Rochester, Kent

Lucas Aerospace
Hemel Hempstead, Hertfordshire

John Curran Ltd
Cardiff, S Wales

Rolls Royce Ltd
Derby, Bristol and East Kilbride

SUMMARY. The RAF started with Avon and Spey Uninstalled Testing Run Up Stands(UTRUS) with limited scope, but soon established firm requirements for the comprehensive UETF facilities which we now have to support Adour and RB199. These have full thrust measurement and comprehensive instrumentation; various developments are described. Data analysis methods are emphasised including the use of desk top calculators and the advantages gained from ADP and Automated Power Plant Testing(APT). CSDE's work on continuous calioration is described, with examples and a brief introduction to their V mask technique. The paper concludes with a description of the RAF Training schemes for UETF Operators.

EARLY DAYS

1. In the early days of jet engines the RAF was deeply involved in all aspects of aero engine repair and overhaul, but when the centrifugal compressor began to give way to axial compressors the Service decided to rely upon civilian industry for this work. Maintenence activitities were limited to control adjustment, replacement of ancilliary components and blending of minor damage to compressor blades. However, it was soon noted that the engines were relatively large within the airframe, and the necessary close cowling created difficulties in checking for oil and fuel leaks and for confirming that there was no gas leakage; an engine removal to rectify any such minor problem was also very time consuming. The obvious solution was a facility for uninstalled engine testing at the operational units, and so the RAF worked with John Currans Ltd early in the 1960s to produce the UNINSTALLED TESTING RUN UP STAND(UTRUS) for the Avon aero engine from our Hunter and Canberra aircraft.

2. These items were very successful, and they provided the impetus for all subsequent RAF developments for uninstalled testing. In principle they consisted of a simple engine support stand, tie downs, fuel supply, a control cabin with instrumentation little more comprehensive than in the aircraft and a tin umbrella to keep the rain away. To keep noise down they were often sited in the middle of the airfield.

THE EARLY SPEY FACILITIES

3. The evolution of modular engines and a growing awareness that returning engines to civilian overhaul facilities tied up many engines in a repair loop and took away valuable potential resources from where they might be useful in times of emergency led us towards tasking our Central Servicing Development Establishment (CSDE) with assessing the possibilities for increased repair capability with the RAF for the Rolls Royce Spey Aeroengines and with defining the extent of the necessary support equipment. Rolls Royce advised that we carry out,Uninstalled Engine Testing after major repairs, such as turbine replacement and gradually the requirements for Spey UETFs firmed up; the following uses were quoted to justify them:

a. Running in the engine after repair.
b. Proving the integrity of the assembly.
c. Setting up the control systems.
d. Checking the thermodynamic and mechanical matching.
e. Confirming that engine performance meets the required In-Service Standards.

4. There was a great resistance towards providing any capability of testing beyond that which could be done in the airframe with aircraft instrumentation, thus the new Spey facilities were denied any immediate capability of checking the thermodynamic matching or of measuring thrust directly. These requirements are still lacking, although the alternative arrangements made have worked well now for almost 14 years. Selected data from the test is provided to Rolls Royce Product Support, who run it through a computor simulation of the engine; in the meanwhile, and provided the engine has achieved all standard performance

figures, the RAF continues with arrangements to issue the engine. By the time we are ready to install it, we normally have clearance from Rolls Royce. You will realise from this procedure that the RAF and Rolls Royce work very much as a team on the Spey.

5. The trend towards deeper servicing and the experiences gained on fully modular types have led us through 4 distinct development steps:

a. No in service repair.
b. LP Cpmpressor and Turbine remove - refit operations at the RAF base, with the item repair at Rolls Royce.
c. Modular remove - refit or replace operations of LPC, HPC, Combustion parts and turbines, but life limits on carcass irrespective of module situations.
d. Fully modular policy with carcase as a module.

We have managed to reach 'd' with a UETF which consisted of an open air test stand under a barn roof on 3 Marks of Spey, but even we've seen the error of our ways and are now working again on the development of thrust measuring arrrngements and better computor support. This latter aspect will be covered in more detail later.

FULL THRUST MEASURING FACILITIES - ADOUR ENGINES

6. Our first fully modular aeroengine was the Adour 102 in Jaguar aircraft. It came into Service as the civilian airlines were also grasping modularity; we heard of them completing turbine or LPC replacements on the wing and the concept of essential UETFs had to be re-argued with the financiers of the day. Military costs are extremely difficult to determine, but logically it seemed to us that:

a. Money would be saved on each engine test if it were completed at the military base rather than by a contractor.
b. Diagnosis on a Military base saves much time out of service for transit, thus fewer spare engines and modules are needed.
c. Preparation, inhibiting and shipment costs are eliminated.
d. An airframe costing ten times that of a UETF is far too expensive to tie up on diagnosis or controls setting.
e. Catastrophic engine failure on test would be less costly in a UETF than in an airframe.

7. These arguements won through, and the RAF obtained more simple UTRUS facilities for Gnome helicopter engines and for Allison T56 turboprops out of our C130s. The benefits of full performance testing and thrust measurement had also been accepted and so the Adour granted support of a full instrumentation package, and for the first time serious consideration was given to an integrated concept of simple transit, installation, fast turn round and computor analysis. (Fig 1)(Fig 2).

DEVELOPMENTS ON ADOUR AND TOWARDS RB199

8. Pre Rigging. The Avon and Spey UTRUS stands are fitted out with the engine on the engine bay and towed to the test location by tractor. The engine carries individual umbilicals which are individually connected. We found this to be extremely inefficient and time consumming. Adours and RB199s have a rigging frame (Fig 3) within a wheeled transportation trolley (Fig 4). All instrumentation are fitted to the engines in the engine bay and connected to coupling plates on the pre rig frame. This takes about 1½ hours. After arrival at the UETF, the pre rig frame plus engine is hoisted off the trolley (Fig 5) into position in the UETF test stand in about 12 minutes (Fig 6). All signal channels and services are automatically connected by mating with a similar coupling plate fixed on the UETF. We have found that 2 pre rigs frames enable us to reduce down time between engine tests to less than 30 minutes.

INSTRUMENTS AND THEIR CALIBRATIONS

9. All instrumentation is calibrated regularly to schedules by CSDE but the RB199 facilities now have the added feature of self calibration of the transducers once the connecting plates are coupled. Known inputs are generated and these are compared with the transponder values; in the event of an out of tolerance bias a microprocessor corrects this during the engine testing. Such facilities have only become possible as we've moved from aircraft style instrumentation to full ADP.

10. Control Room. With time, the facilities with the control rooms have improved enormously. On both Adour and RB 199 Operators have a clear view of the engine through large windows but the styles of instrumentation have evolved dramatically, gone now are the dials of the Spey era, going too are the digital counters of Adour. Now we have RB199 with 3 coloured TV Video monitors upon which all relevant engine and facility parameters are displayed in both analogue and digital form (Fig 7). Illuminated switches control engine start and stopping and every other service. To one side of this is an aircraft MECU which is used for engine control and adjustment throughout the testing and below this the VDU displays all the Performance Data, fully calculated in almost instant timescale and updated many times per second as engine settings are demanded. Our operator technicians have nothing but praise for these developments. The video monitors are clear, and operators much appreciate having both rates of change and discrete data. VDU data allows minute adjustments to control settings to be completed easily and knowledgeably with full control, and the dangers of transcription errors and manual reading are totally gone. The only critisism which frequently arises concerns the throttle. Our operators are adament that they and not some ADP computor must actually control the engine, but using a traditional throttle lever or a lever type position transmitter with detents does not match other facilities. Many would like to see a keyboard selector with a full numerical range of selections of rpm, selection of discrete rates of acceleration demand, inching under operator control about steady conditions by plus or minus x% demands and other facilities; all of this can easily be done on a typewriter keyboard.

ENGINE RUNNING PHILOSOPHIES

11. Uninstalled engine running in the RAF falls into two categories - fault diagnosis and engine performance adjustment and confirmation. At Jaguar and Tornado units the operators identified the following situations for the use of their UETFs:

a. Adour - Engines received from RR are proof run.
- Diagnostic testing is very infrequent.
- Some double checking of pilot reported systems is done particularly for vibrations.
- Dry thrust LP working line is always ascertained.
- Reheat LP working line is always ascertained.
- Engine ratings are normally done on 3 points which takes 20 mins manually cut to 10 mins with ADP.
- Full performance 7 point engine rating is done infrequently, in 50 mins manually and 25 mins with ADP.
- LP Compressor replacements are often not supported by a UETF run.
- UETF test eliminates requirement for an engine air test after installation in the aircraft.

b. RB199 - New engines from RR are not proof run.
- The UETF eliminates any variable intake effect on surge performance.
- Oil consumptions are checked accurately.
- Vibration analysis on the UETF is far better than in the aircraft and the real time analysis of individual rotating assemblies is good.
- LP Blade blending is not supported by UETF run.
- Engines are run to confirm NL Pulse Probe defects.
- Engines are run to reset mecu to counter reports of low NH placard figures from pilots in in max reheat and dry ranges.
- 95% of all UETF running is post strip with module replacement.
- ADP guided test sequencing is marvelous.
- ADP guidance is knowledgeable and flexible saving time, effort, wear and tear and fuel.

12. Data Analysis and Engine Adjustment. The task of reducing the test bed data has been streamlined by the use of desk top calculators, using programmes which the RAF developed for itself at CSDE, and more recently by ADP methods. However, the latest desk top item is still worth description:

a. HP9820 System(Adour). The engine on test is set to a pre determined operating point for dry or wet performance and a 'set' of data is read off the instrument display. This is matched with a card programme and a value of TBT is calculated which co-ordinates to a common thrust value.
Thus the engine is rated and adjustments of control settings on the engine are done as necessary. We find this method is slow and inflexible and to some extent subject to operator dexterity in that curve fits can be 'adjusted' as operators plot their own running line graphs and this can bias the result.

b. HP9826 (New Spey Facility). The Spey facilities are soon to be updated with a programme on a HP9826 system which has also been developed by the RAF at CSDE. This system includes a small VDU and a floppy disc. Thus some ADP facilities can be provided including a menu of instructions on screen. As a simplified sequence, we could have the following:

- Set engine per screen instructions.
- Enter required screen parameters at 2 running points.
- Check and confirm input.
- Run programme.
- Call for comparison of actual engine performances and calculated required performance from datum engine.
- Decide on engine performance standing - Go or No Go.
- Call for print of VDU screen.
- If No Go, call for curser on screen, place on line of graph. (Fig 8)
- Call for display of box indicating area of satisfactory operation.
- Move curser into box.
- Call for read out of information on degree of engine adjustment, shimming or trimming necessary to move engine to Go condition.
- Stop engine on test - adjust.
- Restart engine and repeat.
- Complete multi point runs to fully confirm. (Fig 9)
- Print full data.
- Print log card data with perfect typing and no transcription errors. (Fig 10)
- Store data for return to CSDE monthly for analysis.

This system, particularly for the older engines, is very cost effective saving running time and the associated fuel and manhours. The VDU screen on Spey can display the following:

- T4 v NH
- T4 CoR v NHCoR
- LP W/L
- HP W/L
- LPCACoR v NHCoR
- $NH/\sqrt{T}$ v IGV
- NL v NH
- NL CoR v NH CoR

c. ADP. The Adour and RB199 ADP systems have been accepted by our NCO operators as clearly enormous advances on all previous data display and analysis systems. This is most advanced on RB199 and is under the name 'Automated Power Plant Testing '(APT):

(1) Over 200 signals from pressure transducers, temperature sensing devices, load cells, fuel flow meters, etc are conditioned, digested and displayed continuously on video monitors. Under microprocessor control they are sampled every tenth of a second, checked for validity and for breaching of alarm limits, and passed once a second to the system computer. Corrected and calculated engine parameters are displayed on the top half of a VDU screen. On the bottom half is text which cues the operator through the test advising what condition to set up next, when that condition has been reached and when to proceed to the next step. The computer does not control the test however. The operator can jump steps, change the order of tests or repeat steps if he wishes. The system automatically carries out the performance calculations in seconds and prints out engine control system settings and other log book information.

(2) It also stores a great deal of test information which is subsequently available for analysis by CSDE for establishing trends in engine and UETF performance. The APT system also contains UETF fault diagnosis routines and the ability to simulate an engine on test for training purposes. It has been proved in use that APT reduces the test times by 50% compared with an UETF using traditional instrumentation and a desk top computer. With 2500 gallons of fuel consumed per test such a reduction in testing time is saving the RAF up to £500,000 per UETF per year.

It also picks up discrepancies of many kinds and produces caution, emergency warnings or shut down alarms far faster than are noticed by the operators. However, control is left with the operators and our NCOs find this an excellent service which works well. Over the last 5 years our RAF Service experience with ADP has shown the following real advantages:

- Significant reduction in test times of about 40%. An actual directly comparable sequence has shown a 42% reduction in time and a reduction in fuel used of 51%; clearly manhour costs are saved too.
- Engine life savings - although the RAF does not include UETF running in life consumption, the significant reduction in test time enhances engine longevity for its prime use.
- Improved test repeatability and more consistancy between engines.
- Better and easier compilation of data for subsequent off line analysis at CSDE.

Now we have the RB199 UETFs in service we are finding similar benefits but have no comparative base. I feel however that the very distinct importance of this aspect requires a fuller description of the advantages which we are finding and these are included below:

THE ADVANTAGES OF AUTOMATED DATA PROCESSING ON THE UETF FACILITY

13. The UETF Operators have welcomed the ADP as an enormous step forward. Having a mixture of Adour facilities with normal back up instrumentation alongside the RB199 with the video monitors, we can appreciate not only the value of real time mathematical calculations but also the enormous advances provided on the new displays. In particular the operators praise; the reverse colour display which accompanies warnings and emergency indications, the flexibility of test scheduling, and the much more accurate planning of the testing time-table for forecasting the working day and reducing extended working time. Categorising, the advantages noted are as follows:

a. Engine test times are significantly reduced:

- The use of Automated Powerplant Testing reduces the engine test time compared to manual instrumentation and computations performed on an electronic desk calculator. The time savings occur because the system automatically samples, filters and stores the data for instantaneous display and later analysis.
- The system can be pre-programmed to run through only the specific tests required by the repair action. This eliminates the indexing time for the operator to look up different tests. A menu format is used however and during diagnosis the system is flexible enough for our Supervising SNCO to define a particular sequence of tests and for the operator to be prompted through this sequence.
- A test sequence run automatically to check the correct rigging of the engine before engine tests are started reduces the time required for re-runs.

The by-product of the reduction in test times is the higher throughput of engines for a given facility, a reduction in the fuel used, and the minimisation of the use of engine life. Significant cost savings have been achieved, and the higher throughput has resulted in the elimination of the need for a parallel facility. Significant fuel savings have resulted from reducing the time lost, both when at the test point and between tests; and savings in engine life arise from the reduced operating time, particularly operation at high augmentor power settings.

b. Test repeatability is better:

We are able to consistantly set the engines to their rating point. Consistant rating should result in the engines at their optimum point providing good specific fuel consumption and handling when re-installed in the airframe. The system achieves this repeatability in a number of ways:

- Our NCOs are cued to carry out the same procedure in each test and the system checks that the operation is performed correctly. This reduces incorrect adjustment to the engine caused by faulty procedure or misapplication of limits.
- The data is automatically read and filtered thus eliminating operator error in reading instruments.

- The performance calculations are carried out by proven programmed algorithms on automatically acquired data. This eliminates error on data input, the interpretation of graphical information, and the application of manual correction factors.
- We are able to input modification status of the engine under test and prompt the operator through the correct test procedures with the correct limits for the modification state being applied.
- A software model engine programme provides comparison against actual engine readings at any power setting. This provides positive early indication in the test procedure of problem areas. It also improves recognition of out-of-calibration or faulty tranducers.
- Detailed and complex calibration curves are easily constructed to enhance accuracy and the time required for complete calibration is significantly reduced. However in practice we've had to do some of this work off line because configuration control of the ADP is time consuming.

c. Operator training is easier:

- We are likely to have regular posting of personnel, and a high turnover of staff in the test facility. We need therefore to rapidly train system operators, and to provide management training of supervisory staff with good background of engine knowledge. Training for both levels canbe achieved in the test cell with the system simulating an engine under test. The current simulation is not perfect but is sufficient to provide a realistic read out of the engine test parameters, allows the operator to exercise every mode in the system, and includes the facility to introduce emergency conditions.

d. Operational safety is much enhanced:

The automatic cross checking of the data acquired provides the operator with 'cautionary' and 'alert' indications of unsafe operating conditions. In the event of the 'alert' indication the operator is provided with a check list of corrective actions. This system monitors all the significant parameters at a higher rate and more accurately at the specified limit than can be acheived by an operator with conventional instruments, thus reducing the probability of reaching operating levels which would overstress the engine.

- We are aware that provision can be made to return the throttle to idle a few seconds after an alarm if no other action is taken. The throttle can also be trimmed to prevent excedance of operating limits and the subsequent adjustment required can be indicated. This supports, but does not replace, the experienced operator and at present we prefer to leave a man to mind the store.
- Also a safe shut-down can be programmed to automatically occur on a shut-down alarm, again this is not used.
- Some safety related conditions in the test area are continuously monitored and alarms are activated automatically when safety conditions are not met.

e. Analysis capability is enhanced:

CSDE uses data from all engine testing for various analysis. These are described elsewhere in this paper, but the hard disc copy facility on the ADP provides enormous potential for further work.

f. Manning is reduced:

The significant reduction in test time saves in man-hours required for a test:

- A prompted step-by-step test procedure can be followed by the test operator and supervisor to allow rectification of faults by board replacement. This allows the facility to be self contained. The self test procedure has been designed to be followed by inexperienced personnel, but failures are so infrequent that even dedicated maintenance staff have been unable to gain significant maintenance experience on the system.
- A Test Cell Calibration and Diagnostic Unit (TCDU) is provided for calibration and diagnosis from the engine inter-face connected with a trolley mounted unit. Skills and familiarity with the routines are reduced by automatic calibration routines and automatic logging of results and inclusion in the APT engine test routines.

BED CALIBRATION AND TREND MONITORING

14. Right from the start, when the Spey facilities were produced, it was realised that initial cross calibration with a Master Bed would be needed, plus some form of periodic recalibration of both instrumentation and the total facility. The method chosen was an A B A system: A - Test on Master, B - Test on RAF Bed, A - Retest on Master. With 3 or 4 beds for each engine type to calibrate, we soon realised that we'd be tying up one or more complete engine of each type almost continuously and the cost would be very high. Some attempts were made to drop the recalibrations. A spate of Spey engine rejections off test soon gave us food for thought: we discovered that minor changes in instrumentation and unauthorised modifications to the facility caused uncontrolled drift in pass-off results. One such cause, for example, was the fitment of a workmans ladder inside the test compound. In 1978 the CSDE was tasked with developing a formal method by which the UETFs could be monitored continuously, thereby eliminating any need for recalibrations.

15. Data is now sent to CSDE from every engine run completed on every RAF test bed and continuous records of various parameters are maintained. Data from simple rigs is a paper roll print out of rating points; from HP9826 facilities we print out a monthly data listing on floppy disc; while from the ADP beds a hard disc pack of data is provied. Some examples of these are included in the figures:

a. Adour 151 Cusum data for RAF Brawdy. (Fig 11)
b. Adour Histogram of T4 banding. (Fig 12)
c. Adour Mass Plots of T6 UTS T4. (Fig 13)
d. Adour 151 Performance data by module change. (Fig 14)
e. Adour 104 Time Averages of Performance Data 1 Base. ~~(Fig 15)~~ *
f. Adour 104 Performance Averages - Various Bases. ~~(Fig 16)~~ *
g. RB199 NLC vs NHC. (Fig 17)
h. RB199 MFC Histogram comparing 2 bases. ~~(Fig 18)~~ *
j. RB199 SOTC Histogram comparing 2 bases. ~~(Fig 19)~~ *

These plots and averages can be scanned for trends.

16. Undoubtably the best technique has involved Cumulative Summation Techniques (CUSUM). Put simply the effect of each new wngine result is added to the average of all previous summations and continuous plots are maintained. Any disturbance in the direction of a plotted line indicates that the latest set of results is deviant in some way. Any test facility generating an instrument fault or change of air flow, or drift or transducer soon shows up and analysis of various data combinations has pinpointed faults. Some examples of those are included in the figures:

a. RB199 Cottesmore 19 Oct 83 plot - M1CoR goes wild, other parameters change drift - fault was transcription of 2 pressure tapping pipes. (Fig 20)

b. RB199 Cottesmore 24 Jun 83 - T1 goes wild on 5 May - fault was incomplete coupling of pre rig stand. (Fig 21)

c. RB199 all units 11 May 83 - MFC goes wild on 1 Feb 83 - fault was a defective fuel meter.(Fig 22)

d. Adour 104 Bruggen 20 Oct 83 - T4 fall off fault was poor recalibration of P3 gauge. (Fig 23)

17. CSDE have developed computer masking technique using a V shape superimposed on the data line. A plot which crosses the mask sets up an alarm and subsequently closer analysis is completed. I feel CSDE could present a fuller paper on such techniques to AGARD. The overall result of this work is that the RAF no longer needs to complete any periodic recalibration.

18. Engine Fleet Performance Trend Monitoring. Using the data base described above CSDE is also able to trend the whole fleet and identify any change in fleet wide standard. For instance, we have monitored for tendencies to raise T4 in order to hold rated thrusts as the fleet ages, and tracked the long term average effect of a modification. Again CSDE could give their own presentation on this aspect. At Units, SNCOs often maintain their own data too, and for instance at RAF Honnington a hard copy is taken of all test runs. Apparently quick skimming through 'by eye', seeking for comparable engines, helps to solve problems and provides understanding of data formats and enhances familiarity with nomenclature for rapid understanding of screen displays.

TRAINING

19. The operators of RAF UETFs are invariably fully trained and experienced Propulsion Technicians who have undertaken further specialist training in UETF operation and Propulsion Theory. They are supported by Ground Equipment Specialists and Electronics Specialists - L Tech(Flight Systems) for the ADP. The first step in the UETF training for RB199 testing is a refresher on electrical and electronic principles at No 1 School of Technical Training RAF Halton. Phase 2 concerns RB199 documentation and is at RAF Cottesmore. Phase 3 is an RB199 engine course at Rolls Royce Bristol. This far, the training is generally valuable for any RB199 Propulsion Technician but following on at Phase 4 we have a specialist lead-in, ETH course at RAF Halton, Phase 5 is for specialist ADP equipment. Further familiarisation, and training is given at the operational units (OJT). The ETH course covers the following:

a. 2 days revision on mathematics and programmable calculators.
b. 3 days Propulsion Theory on thrust generation, non dimensional analysis, engine and module performance, multi spool performance.
c. 5 days analytical study of RB 199 results from UETF.
d. One day Vibration and X-Y Plot Results.
e. Course Visit CSDE.

At the operational units, the OJT is greatly assisted by acess to a Training Capability within the ADP and with the step-by-step guidance given to the operator by the friendly software. In the training mode, a complete engine test can be simulated without even having an engine mounted in the test cell. Using a software model within the computer, a trainee can 'run' this engine starting with various options while an instructor can trigger various alarms. At the present time this ADP mode is still being developed further, and we're looking forward to even greater usefulness.

THE FUTURE OF ENGINE TESTING

20. We already have, in the RB199 UETF, the worlds most advanced in-Service test facility (Fig 24). We are in the process of buying two Helicopter Universal Engine Test Houses (HUETH) which will test both Chinook and Puma engines up to full power against high speed dynometers. They are capable of modification to test other turboshaft engines up to 4500 shaft horsepower. Under discussion is the need for a UETF for the Pegasus engines of present and future Harriers. The nature of the aircraft means that it is 'thrust critical' and its design makes abortive engine fitment costly in manhours and aircraft downtime. Although it is argued that meaningful engine performance tests can be carried out with the engine installed in the aircraft, it makes a very noisy, expensive and less than satisfactory test facility and superimposes onto the test airframe related deviations which are impossible to standardise or maintain constant. Even though 4 separate nozzles make difficulties, there are many advantages in favour of a UETF for Pegasus too.

* Figure withdrawn

CONCLUSION

Uninstalled engine testing is now an established feature of engine maintenance in the RAF. We consider UETFs are an essential adjunt to our In-Service repair capability. But they have overriding, intrisic values to which I have alluded. UETFs give us the ability to test engine performance thoroughly and cheaply without risking a £10M airframe. We can also monitor fleet wide performance of engines by measuring and calculating critical parameters at standard conditions with a degree of accuracy simply unattainable from installed testing. This has enabled us to optimise the engine life versus performance trade-off whilst ensuring the safe operation of the engine; above all, they have given us the confidence that the engine will deliver the performance that the pilot both needs and expects after module replacement, on base and by RAF tradesmen.

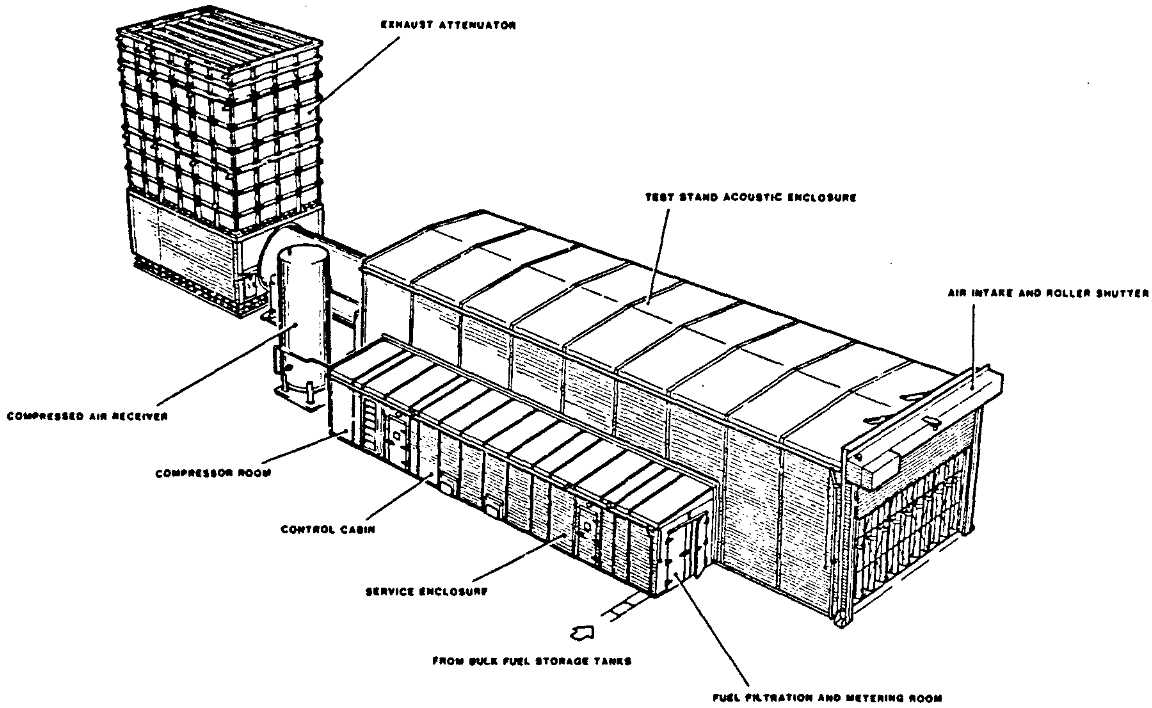


Figure 1 General layout of the test facility

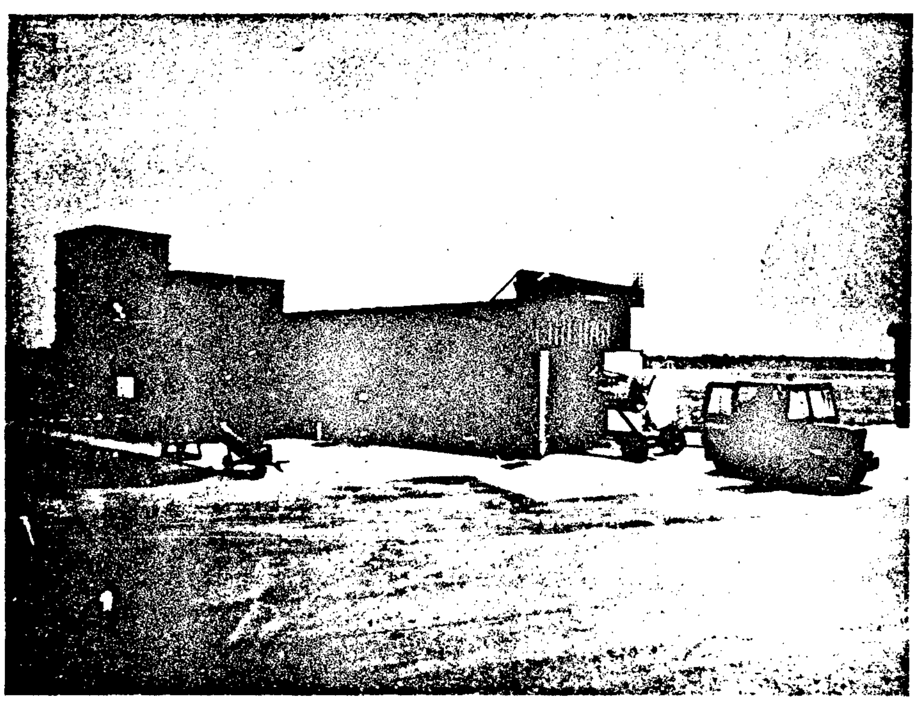


Figure 2 Adour 102 engine test facility--RAF Coltishall

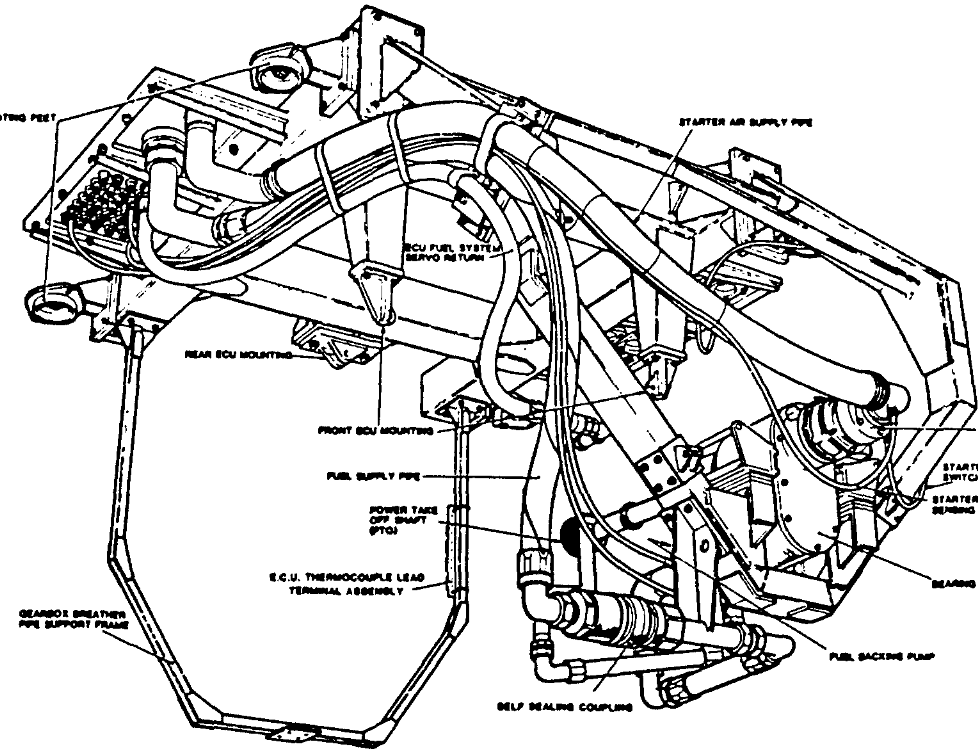


Figure 3 Pre rigging frame

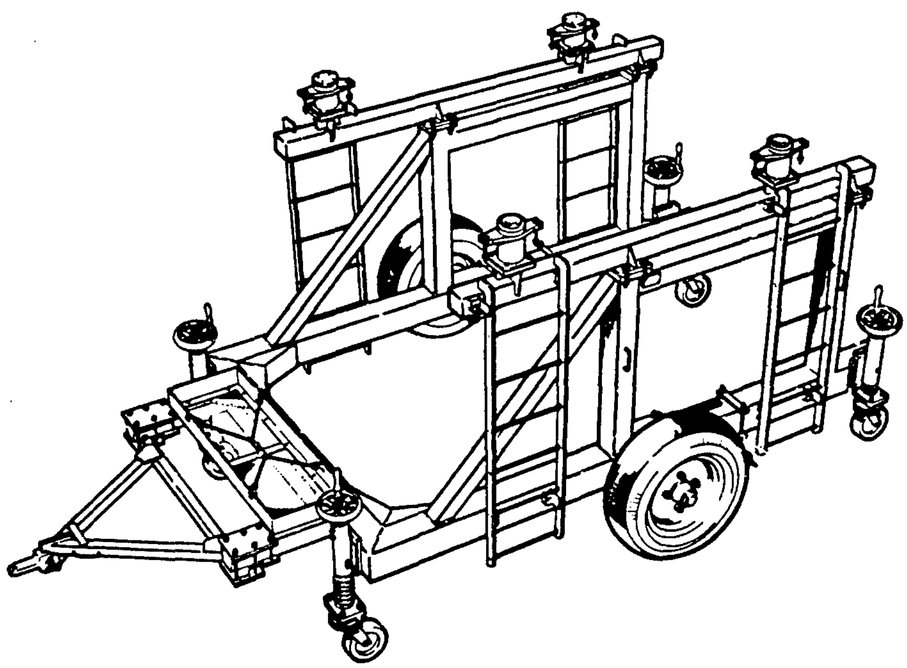


Figure 4 Transportation and rigging trolley

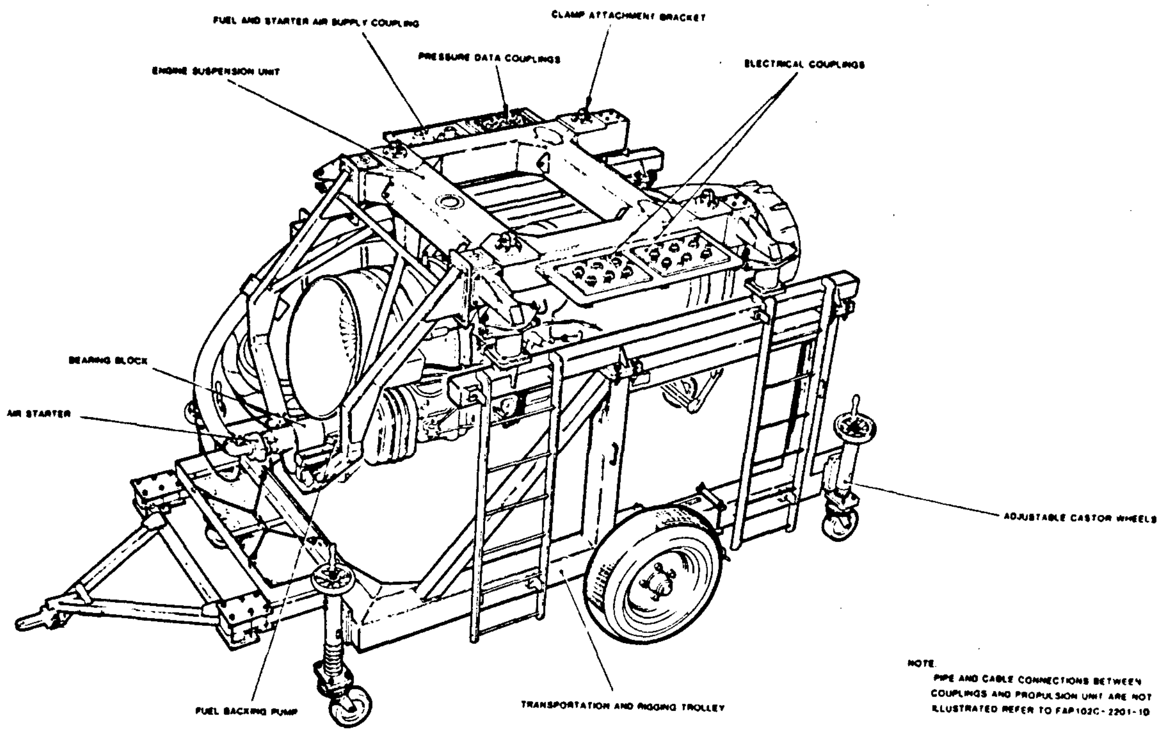


Figure 5 Pre rigged ECU and trolley

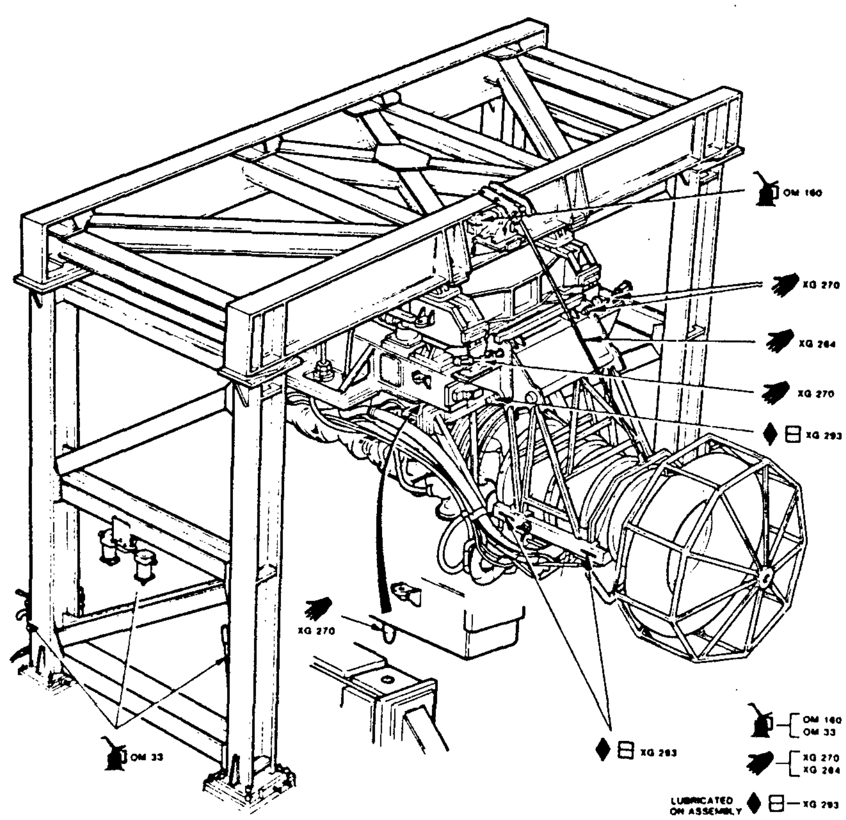
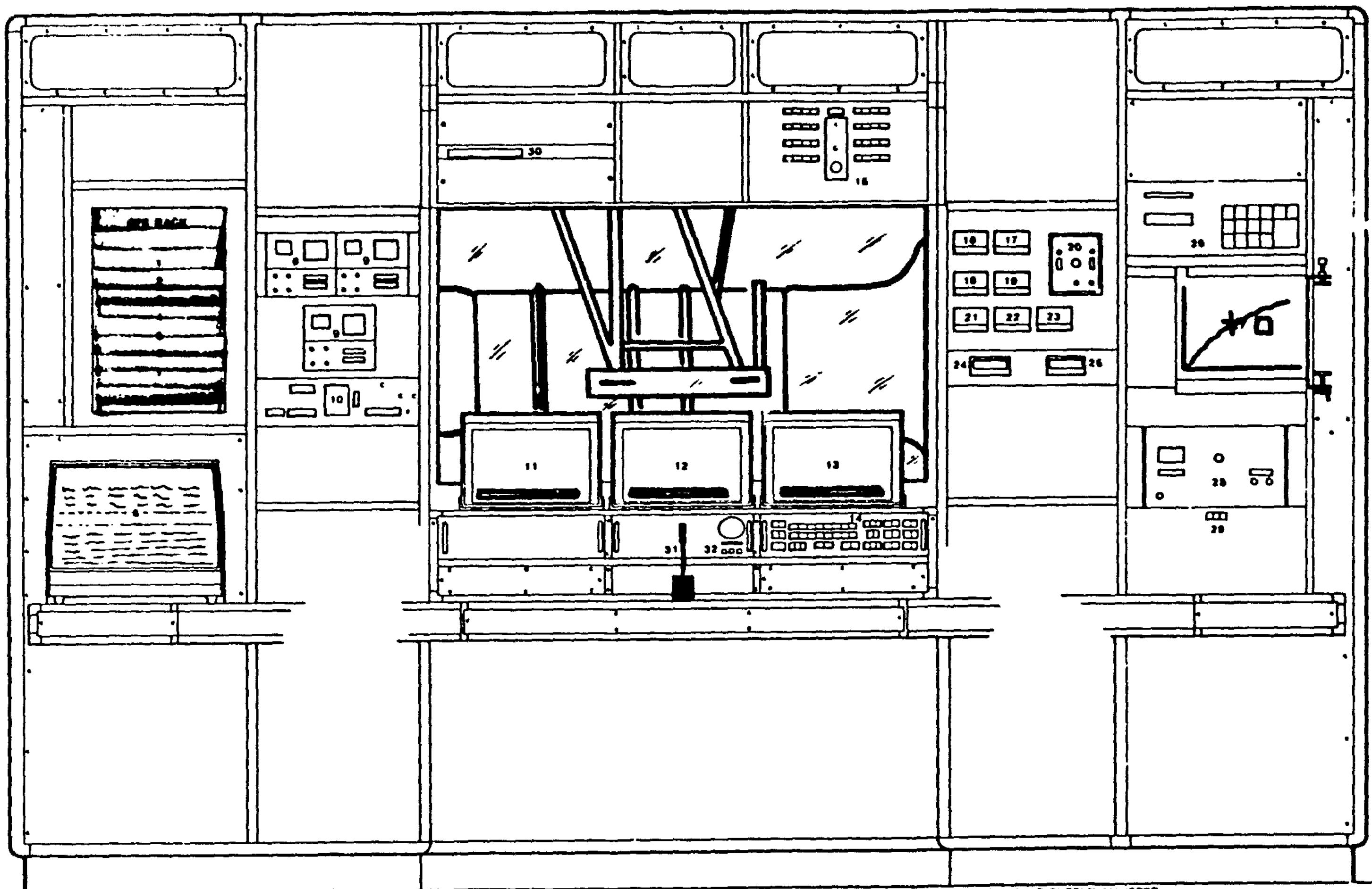


Figure 6 Test stand assembly



1 ECU MAIN ELECTRONIC CONTROL UNIT
2 NL/NH OVERSPEED GOVENOR AMPLIFIER
3 ECU VIBRATION WARNING AMPLIFIER
4 TURBINE BLADE TEMPERATURE AMPLIFIER
5 JET PIPE RESONANCE AMPLIFIER
6 AFTERBURNER DETECTION AMPLIFIER
7 FUEL FLOW INDICATOR (AIRCRAFT TYPE)
8 VISUAL DISPLAY UNIT AND KEYBOARD
9 TCDU DIGITAL PRESSURE INDICATOR
10 TCDU PRECISION DC SUPPLY UNIT
11 LH VIDEO UNIT
12 CENTRE VIDEO UNIT
13 RH VIDEO UNIT
14 ECU CONTROL PANEL SEE FIG.3
15 GENERAL SERVICES CONTROL PANEL SEE FIG.4
16 28V DC ECU SUPPLY VOLT METER
17 28V DC ECU SUPPLY AMMETER
18 28V DC GENERAL SERVICES SUPPLY VOLTMETER
19 28V DC GENERAL SERVICES SUPPLY AMMETER
20 ICE DETECTION CONTROL UNIT
21 115V 400HZ SUPPLY VOLTMETER
22 115V 400HZ SUPPLY AMMETER
23 115V 400HZ SUPPLY FREQUENCY
24 DIGITAL INDICATOR "AIR PRESSURE AT STARTER"
25 DIGITAL INDICATOR "AIRLINE PRESSURE"
26 VISICORDER
27 XY PLOTTER
28 REAL TIME ANALYSER
29 ECU VIBRATION AND FAN FLUTTER SELECTORS
30 TIME OF DAY CLOCK
31 ECU REV/MIN CONTROL LEVER (PILOTS LEVER)
32 INTERCOM CONTROL PANEL

Figure 7 Control console and display

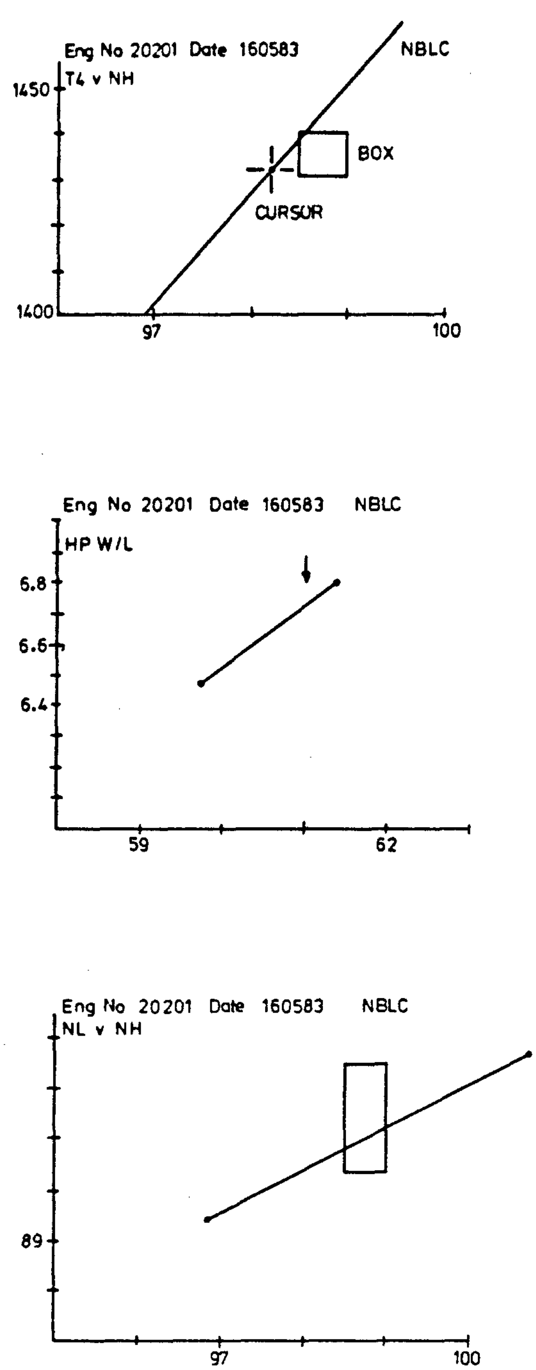


Figure 8 Spey 202 HP9826 Display (1)

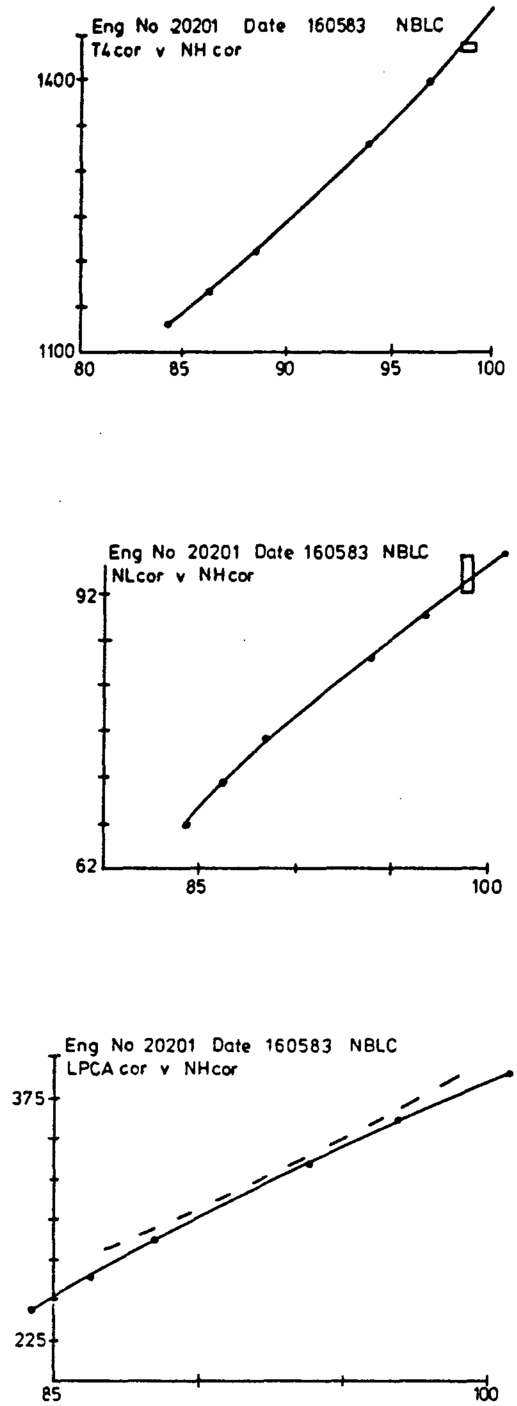


Figure 9 Spey 202 HP9826 Display (2)

SPEY Mk 202/203 ENGINES

Engine No 20201 Date Tested 160583 Jet Pipe No AU291

GOVERNOR SETTINGS

HP GOVERNOR	94.5%		
NON BLC T6	687degC	TRIMMER RESISTANCE	115.0 ohms
7TH BLC T6	5degC	TRIMMER RESISTANCE	5.0 ohms
12TH BLC T6	5degC	TRIMMER RESISTANCE	5.0 ohms
T3 LIMITER RESET	416degC	TRIMMER RESISTANCE	111.7 ohms

NH/√T1 SCHEDULING | 5% 3.650 | 60% 4.500 | 95% 5.800 |

HP IGV ANGLE SETTING | 4.00 to 44.00 |

CONTROL SETTINGS AND ADJUSTMENTS

MAX SPEED STOP ADJUSTMENTS	NIL	TURNS
MAX TRIM STOP ADJUSTMENTS	NIL	TURNS
MIN TRIM STOP ADJUSTMENTS	NIL	TURNS
IGV & BV GOVERNOR GAP	0.004	INS
MAX REHEAT STOP GAP	0.000	INS

PRCU SETTINGS

AT 5.45NH/√T1

R/H UNLIT A/C SERVICES.X2 POSITION	75.9
LP SPEED CHANGE R/H UNLIT TO LIT	1.02

AT 5.66NH/√T1

R/H UNLIT A/C SERVICES.X2 POSITION	79.1
LP SPEED CHANGE R/H UNLIT TO LIT	0.92

CORRECTED LP COOLING AIR TEMPERATURE

HP RPM	CAT
95%	347
92.5%	325
90%	302

PRCU ADJUSTMENT

	PROJECTION
X2	0.000
X6AUX	0.000
X6AX	0.000

PRCU SERIAL No
IGV ANG

SPECIAL DETAILS

THIS ENGINE REQUIRES A JET PIPE WITH MOD JP1083 EMBODIED

Figure 10 Spey 202 log card from HP9826

Engine Cusum Data RAF BRAWDY Adour 15101

Date-29Sep83 Engine No-5081 Hours- 723.10 PASSED

Modules changed 4 7

Mods 364 429 491 392 571 650 592 677

TOTALvib	21.0000	HP vib	19.0000	LP vib	6.0000	adp	0.0000
NA	0.0000	T1	288.5500	LP W/L	2.2302	HP W/L	3.8978
XG	5100.0000	T6	983.2309	T4	1388.0566	T3	610.6984
T2H	385.6600	NH	100.6302	NL	99.9025	M1	92.6895
M2	49.6834	FE	1.0699	P2M/P1	2.3019	P2H/P1	2.3337
P3/P1	10.3886	P3/P2H	4.4525	P8/P1	2.0307	T3/T1	2.1189
BPR	0.8656	NH/NL	1.0073	T4-T6	404.8257	T2-T1	97.5100
T3-T2	225.0383	SFC	0.7552	OVER/EFF	81.9508	HP EFF	88.8273
LP EFF	82.2684	NA*P8/P1	0.0000	LPNGVMIX	36.0000	AIRMETER	15.0000
HPNGVMIX	72.0000	FLOWTIME	203.1053	spare	0.0000	spare	0.0000

Figure 11 Typical Cusum data to CSDE (Adour 15101)

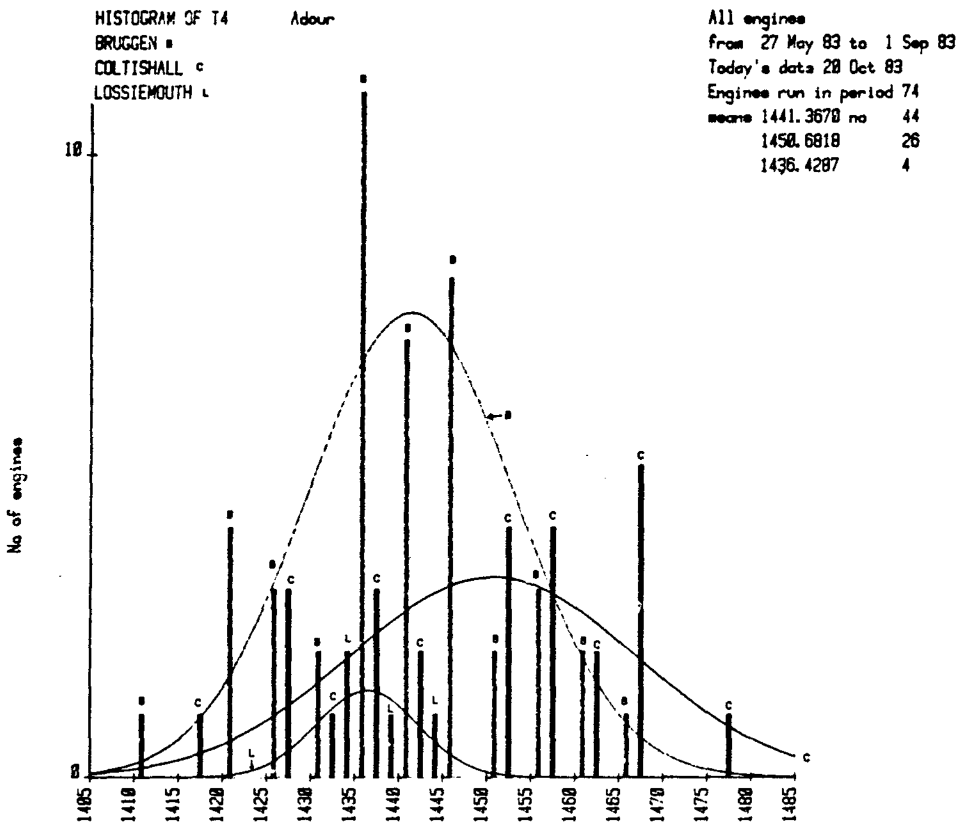


Figure 12 Adour histogram of T4 banding

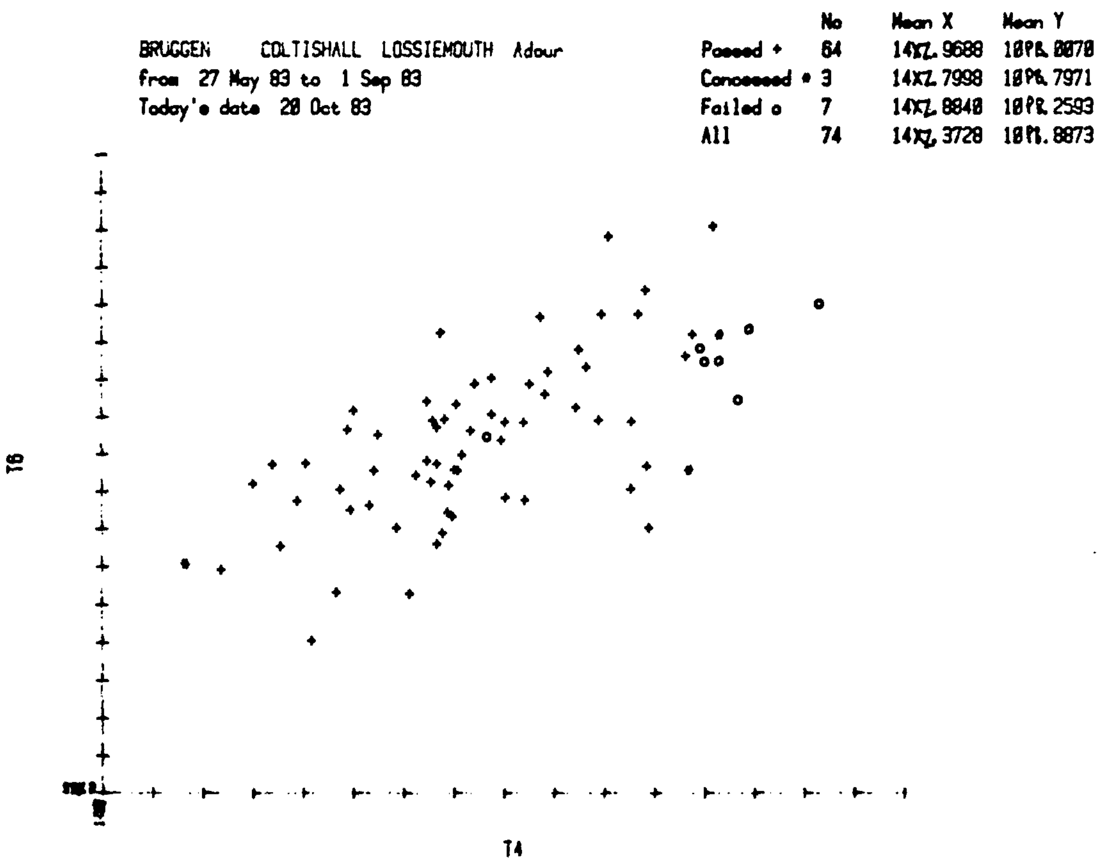


Figure 13 Adour mass plot of CSDE data

PERFORMANCE ANALYSIS OF RETESTED ENGINES

ADOUR MK 151

LIST OF MODULES

1 LP COMPRESSOR 1
2 LP COMPRESSOR 2
3 INTERMEDIATE COMPRESSOR CASE
4 HP COMPRESSOR
5 HP NOZZLE GUIDEVANES
6 HP TURBINE ROTOR
7 LP NOZZLE GUIDEVANES
8 LP TURBINE ROTOR
9 EXHAUST MIXER
10 HS GEARBOX
11 OIL TANK SYSTEM
12 AFTERBURNER

PASS CODES

0 Failed
1 Passed
2 Concession
3 Mechanical
4 Performance
5 Vibration
6 Reheat
7 Accessories

From 1 Jan 82 to 20 Oct 83 Today's date 20 Oct 83

ENGINE NO/HRS	DATE	PASS CODE	MODULES CHANGED	T4	Delta	T6	Delta	PR	Delta
5020									
1079	14 Apr 82	1	000010101000	1349.043	0.0000	977.774	0.0000	1.014	0.0000
136	27 Jul 83	1	000011101000	1363.248	14.2047	993.608	15.8342	1.031	0.0166
Mean values				1356.145		985.691		1.023	
5113									
1135	15 Nov 82	1	000000000000	1368.982	0.0000	961.950	0.0000	1.024	0.0000
1135	4 Jan 83	1	110011111000	1316.404	-52.5781	955.758	-6.1918	0.953	-0.0710
Mean values				1342.693		958.854		0.988	
5112									
834	19 Mar 82	1	100110110000	1362.453	0.0000	988.197	0.0000	1.021	0.0000
1033	17 Jan 83	1	100110111000	1350.201	-12.2517	976.040	-12.1577	1.017	-0.0038
Mean values				1356.327		982.118		1.019	
5200									
400	23 Apr 82	1	100010010000	1367.250	0.0000	974.400	0.0000	1.015	0.0000
500	5 Oct 82	1	100110000000	1350.940	-16.3102	971.017	-3.3831	1.011	-0.0037
Mean values				1359.095		972.709		1.013	

Figure 14 Adour 151 performance analysis after module change

Figures 15 and 16 withdrawn

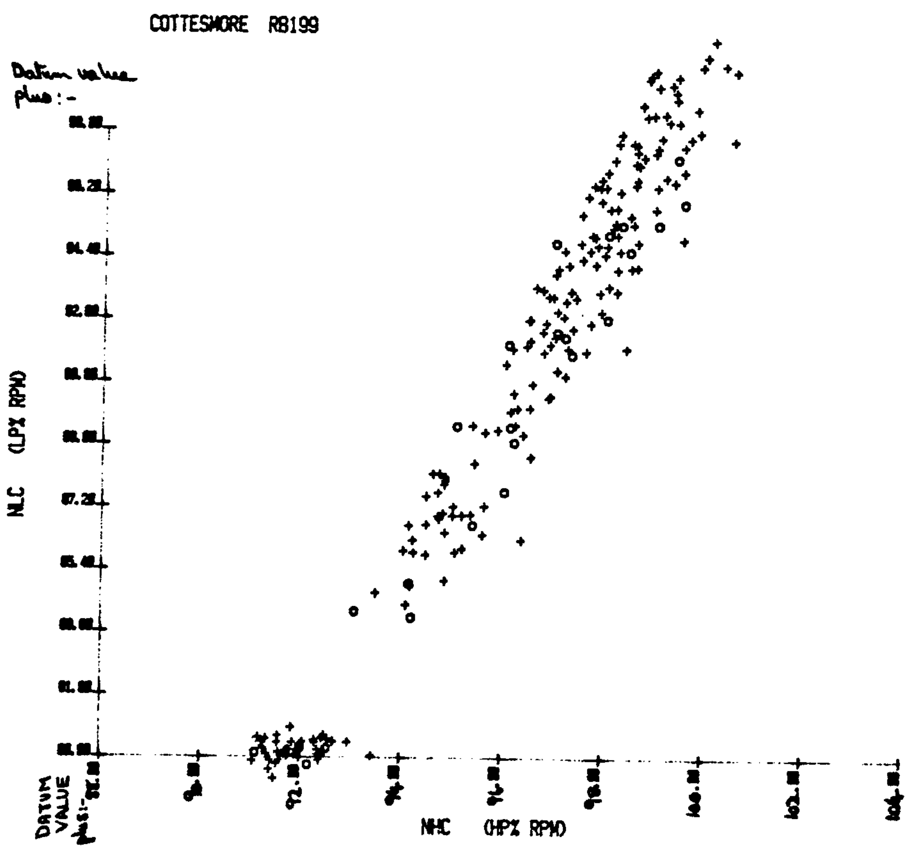


Figure 17 RB199 mass plot of CSDE data

Figures 18 and 19 withdrawn

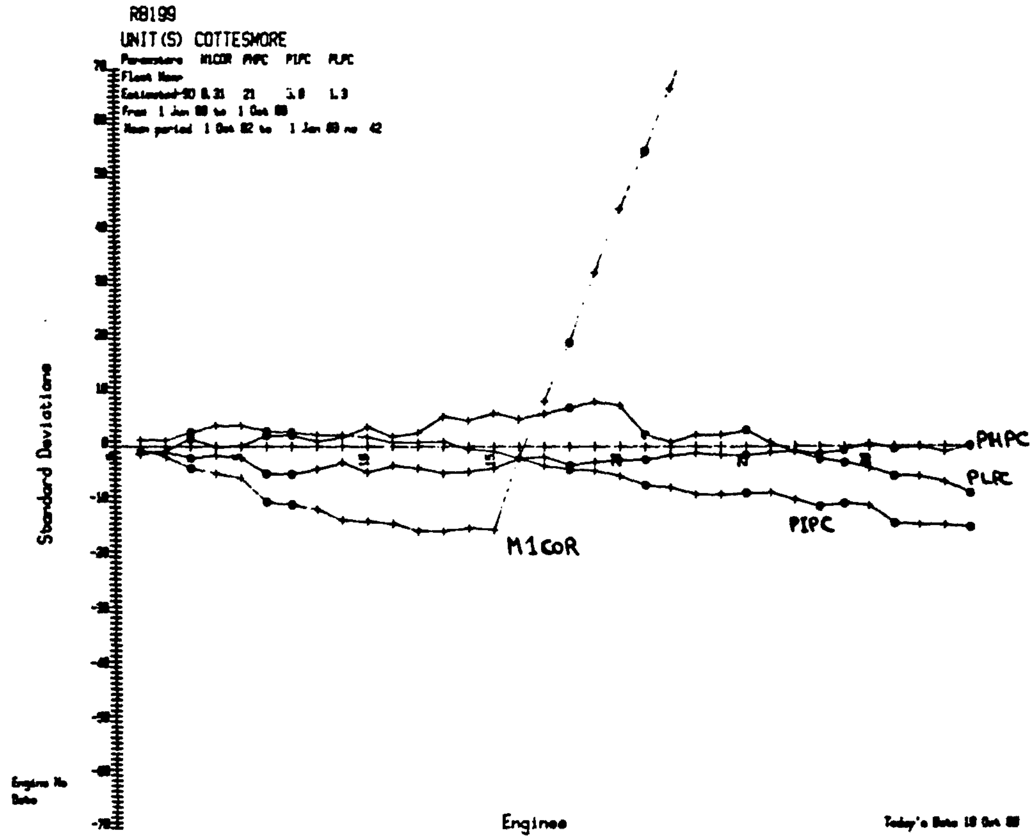


Figure 20 Cusum plot RB199 (1)

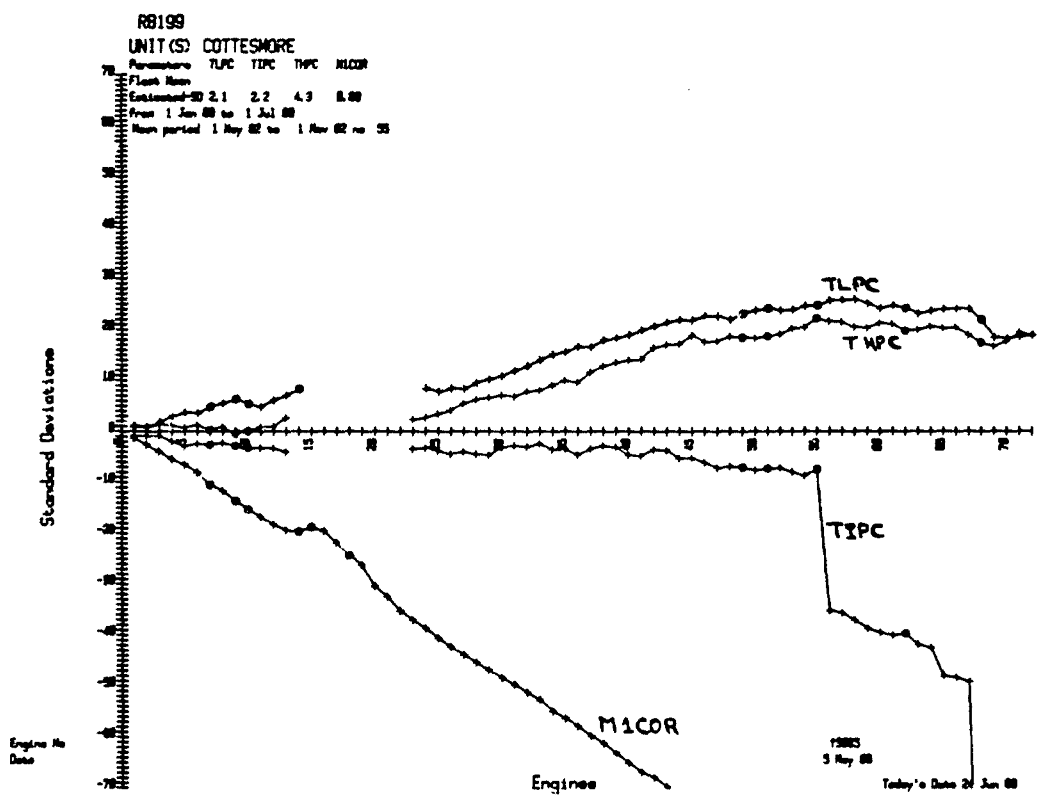


Figure 21 Cusum plot RB199 (2)

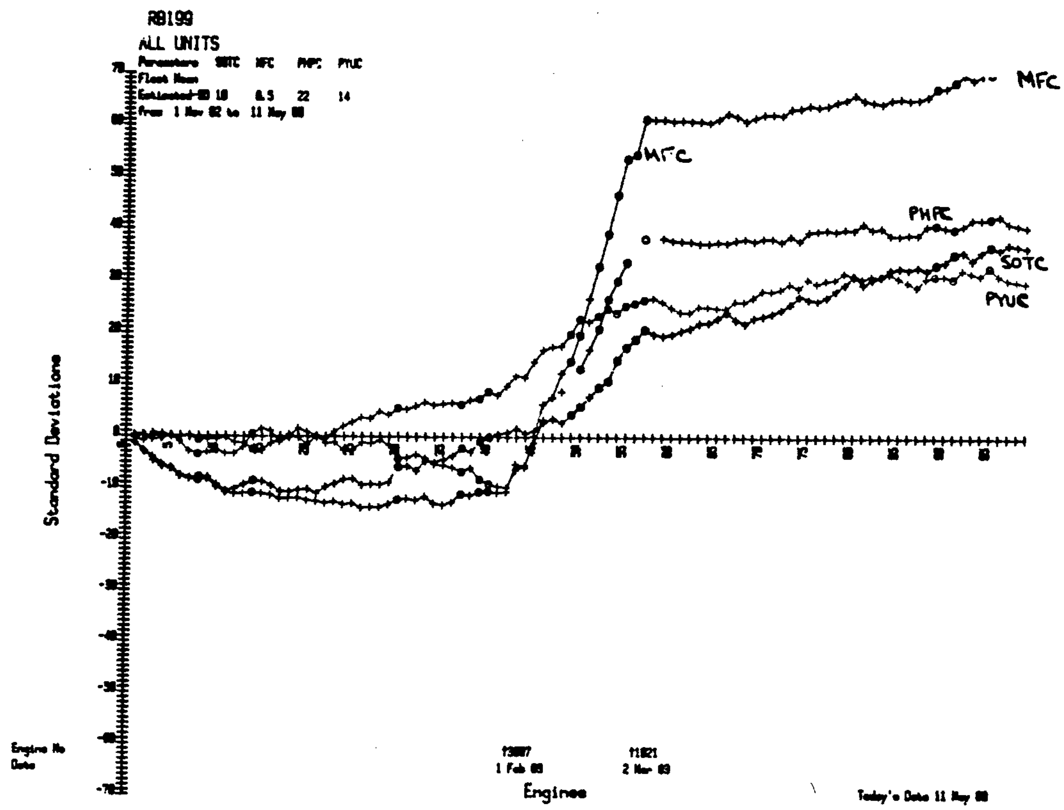


Figure 22 Cusum plot RB199 (1)

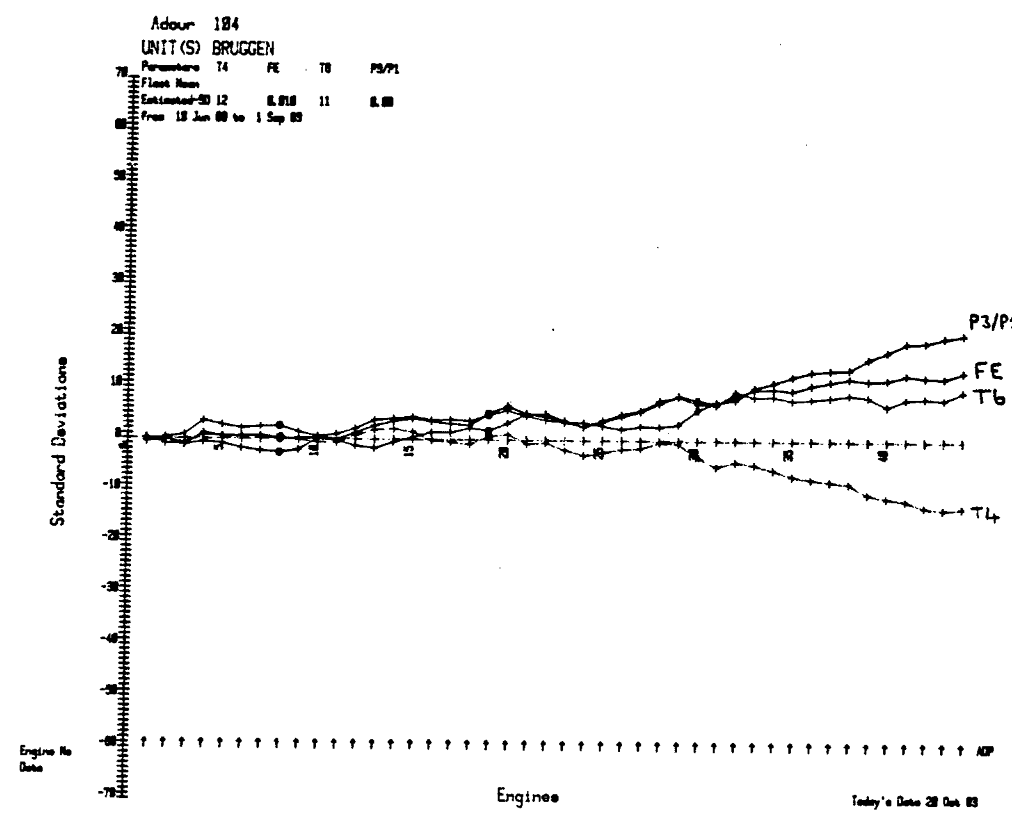


Figure 23 Cusum plot Adour

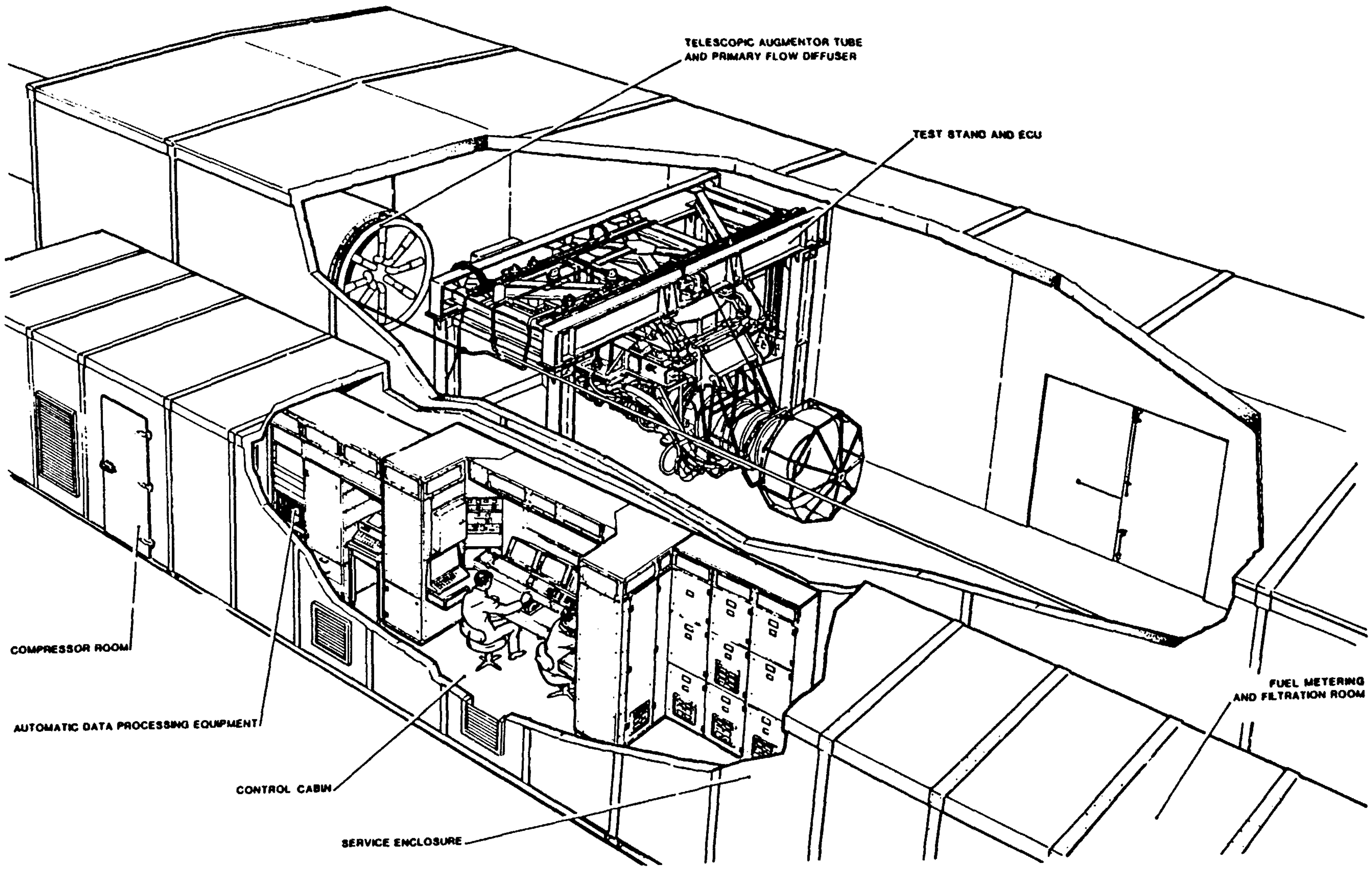


Figure 24 RB199 test facility layout

BIBLIOGRAPHY ON ENGINE TEST FACILITIES

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Lecture Series Director

AGARD Lecture Series 132

BIBLIOGRAPHY ON ENGINE TEST FACILITIES

INTRODUCTION

This bibliography has been prepared by the Defence Research Information Centre of the UK Ministry of Defence (Procurement Executive) in collaboration with Mr P F Ashwood, Director, Lecture Series No.132.

The bibliography was compiled using the NASA aerospace file based on the NASA abstract bulletin, Scientific and Technical Aerospace Reports (STAR) and the American Institute of Aeronautics and Astronautics publication International Aerospace Abstracts (IAA).

The items are listed under five main headings, but this division is purely arbitrary, as many of the items do not fall clearly into a single classification. This is particularly true in the fields of instrumentation and test techniques.

References dealing with engine noise measurement have been omitted as this is a specialised subject outside the scope of the present Lecture Series. However reports dealing with test techniques such as the use of X-rays to observe tip clearance and the design of rigs to impose gyroscopic forces on engines have been included, for whilst they are not widely used they do have a place in engine development testing and hence are relevant.

Selection of items have been based on the title and published abstract only; whilst this can occasionally be misleading there is no reasonable alternative. Differences in terminology also produce difficulty. For example, in the USA, testing in altitude facilities is often referred to as 'ground level testing', meaning the use of a ground-based facility in contrast to in-flight testing. In the field of instrumentation and data processing this difference is not significant as most of the techniques are equally applicable to ground level test beds and altitude test cells; several references concerned with altitude testing have therefore been included.

Items of the form 83N12345 are from the NASA-STAR and copies of these are generally available from NASA or from British Library Lending Division, Boston Spa, Wetherby, Yorkshire, England. NASA-originated and NASA-sponsored documents may be purchased by European requestors, in microfiche form from ESA - Information Retrieval Service European Space Agency, 8-10 rue Mario - Nikis, Paris, France.

Items of the form 83A12345 are from IAA. These are of published literature and the source is generally quoted in the reference.

The five group headings are:

1. General
2. Test facility design
3. Test techniques
4. Instrumentation
5. Performance evaluation

1. GENERAL

1. 83A29277
EVALUATION OF THE PRODUCTIVITY OF AN AUTOMATED SYSTEM FOR THE TESTING OF AIRCRAFT ENGINES
Otsenka proizvoditel'nosti avtomatizirovannogo^tekhnologicheskogo kompleksa ispytanii^aviatsionnykh dvigatelei
Berkheev, M. M.
Aviatsionnaia Tekhnika no. 4, 1982, p. 20-24. In Russian.

The paper proposes a method for calculating the productivity of an automated system for the testing of aircraft engines based on the use of closed stochastic queueing networks. An algorithm and program were developed for calculating the efficiency of automatic testing systems of various structures. Particular attention is given to a two-level system that uses one minicomputer and two combined minicomputers on the first level and one minicomputer on the second level.

Controlled Terms: *AIRCRAFT ENGINES / ALGORITHMS / *AUTOMATIC TEST EQUIPMENT / COMPUTER PROGRAMS / *ENGINE TESTS / MINICOMPUTERS / NETWORK ANALYSIS / *PRODUCTIVITY / QUEUEING THEORY / STOCHASTIC PROCESSES / *SYSTEM EFFECTIVENESS / SYSTEMS SIMULATION / *TEST STANDS

2. 82A35048
T700 - MODERN DEVELOPMENT TEST TECHNIQUES, LESSONS LEARNED AND RESULTS
Dangelmaier, R. A.
AIAA Paper 82-1183, AIAA, SAE, and ASME, Joint Propulsion Conference, 18th, Cleveland, OH, June 21-23, 1982, AIAA 10 p.

The testing of the T700 engines is discussed. The 300-hr model qualification test required the engine to withstand low cycle fatigue cycles, thermal cycles, ingestion of various objects and substances including liquid water, ice, sand, and birds, and to meet hot and cold start criteria. The engine was measured for overtemperature, smoke emission and corrosion susceptibility. Abusive vibration testing, inlet and exhaust system evaluation, and suction fuel system examination was also done. Pre-production engine ground and flight testing was done in a number of aircraft. This was followed by a two-year maturity/life verification program in order to further assure a high level of life, durability, reliability, and maturity at the time of production introduction in 1978. Accelerated endurance and accelerated mission testing was done. Problems uncovered and corrected during the testing are discussed.

Controlled Terms: *AIRCRAFT ENGINES / CORROSION TESTS / *ENGINE TESTS / *FATIGUE TESTS / *FLIGHT TESTS / FUEL SYSTEMS / *GROUND TESTS / PRODUCT DEVELOPMENT / QUALITY CONTROL / RELIABILITY ANALYSIS / SERVICE LIFE / TEMPERATURE MEASUREMENT / *THERMAL CYCLING TESTS / VIBRATION TESTS

3. 82A35049
NEXT GENERATION TRAINER /NGT/ ENGINE REQUIREMENTS - AN APPLICATION OF LESSONS LEARNED
Bauer, C. J.
AIAA Paper 82-1184, AIAA, SAE, and ASME, Joint Propulsion Conference, 18th, Cleveland, OH, June 21-23, 1982, AIAA 7 p.

A new, four-step approach for turbine engine development is described, as well as the new Engine Structural Integrity Program (ENSIP). Instead of the former two-step qualification process including a preliminary flight rating test and a model qualification test, the new concept emphasizes definition and verification of field maintenance procedures and parts life limits. It includes an initial flight release, full flight release, initial service release, and operational capacity release, each of which is briefly described. ENSIP encompasses five tasks: (1) design information; (2) design analysis, component and materials characterization; (3) component and core engine testing; (4) ground and flight testing; and (5) product quality control and engine life management. The integration of the former procedure with the new concept and procedure is discussed.

Controlled Terms: *AIRCRAFT ENGINES / *AIRCRAFT MAINTENANCE / COMPONENT RELIABILITY / COST REDUCTION / DESIGN ANALYSIS / ENGINE PARTS / FLIGHT TESTS / GROUND TESTS / *LIFE CYCLE COSTS / QUALITY CONTROL / *RELIABILITY ENGINEERING / SERVICE LIFE / *TECHNOLOGICAL FORECASTING / *TRAINING AIRCRAFT / *USER REQUIREMENTS

4. 82N10063
AIR-BREATHING ENGINE TEST FACILITIES REGISTER
Krengel, J. H.
Advisory Group for Aerospace Research and Development, Neuilly-Sur-Seine (France).
AGARD-AG-269 122 p.

A register was compiled, aimed at comprising the test facilities relevant for research and development in NATO countries. Included are test facilities being in use or under construction at the various research organizations, industrial firms, and universities. Test facilities and their technical data are given as far as the response to a questionnaire was received or open literature was available. Test engineers will be able to find whether a test facility suiting their specific demands already exists or may be easily adapted to their purposes.

Controlled Terms: *AIR BREATHING ENGINES / AIRCRAFT ENGINES / ENGINE TESTS / LISTS / *REGISTERS / *TEST FACILITIES

5. 81A34159
A FORWARD LOOK AT GAS TURBINE TESTING FACILITIES
Webb, W. L.
SAE Paper 80-1124 Society of Automotive Engineers, Aerospace Congress and Exposition, Los Angeles, Calif., Oct. 13-16, 1980, 10 p.

Requirements for future high thrust-to-weight gas turbine engine testing facilities and the parameters that generate them are reviewed. Much longer in-service life of future engines than those of the past, and higher thrust-to-weight and lower fuel consumption compared to earlier engines require a more demanding development and in-service support testing. Testing facilities must be capable of fulfilling the testing objective to meet the in-service performance, availability and durability, and they must be capable of completing these objectives in an economical manner. Specific requirements for full engine test facilities include (1) thrust ranges from 500 to 50,000 lbs plus transient response capability of 10,000 lb sec; and (2) for afterburning engines, the capability to manage exhaust gas temperatures in the range of 3000 F. Improved simulation technology will improve the design cycle, and the controls development can be improved with expanded control development facilities, which should be capable of testing the control system's functional operation in an environment that duplicates that of the engine.

Controlled Terms: *ENGINE TESTING LABORATORIES / ENVIRONMENT SIMULATION / FULL SCALE TESTS / *GAS TURBINE ENGINES / *TECHNOLOGICAL FORECASTING / *TEST FACILITIES / THRUST-WEIGHT RATIO / VARIABLE CYCLE ENGINES

6. 81N24084
TURBINE ENGINE TESTS AS SEEN BY AN AIRCRAFT COMPANY
les essais reateurs vus par une compagnie^aerienne
Chetail, P.
Air France, Paris.
Service des Etudes de Propulsion. In AGARD Turbine Engine Testing 13 p.

The need for conducting specific tests on turbine engines using ground test stands was felt not only after inspection, but also at the time of their installation in the aircraft and before their being placed in the shop for repair. Monitoring the performance degradation of engines in the course of service appears to be complementary and very desirable and should become possible by virtue of the semicontinuous recording of parameters on the aircraft, as well as by advanced performance analysis such as the GRA which, on the most recent type of civil turbines, permits more reliable evaluation of engine performance at the level of principal modules than is provided by classic methods.

Controlled Terms: AUTOMATIC TEST EQUIPMENT / DATA RECORDING / *ENGINE TESTS / *IN-FLIGHT MONITORING / *MAINTENANCE / MONITORS / *PERFORMANCE TESTS / TEST STANDS / THRUST / *TURBINE ENGINES

7. 81N24104
PREDICTION OF FUTURE TEST NEEDS, TEST FACILITIES AND PROCEDURES
Abell, E. E.
Aeronautical Systems Div., Wright-Patterson AFB, Ohio.
In AGARD Turbine Engine Testing 4 p.

The requirements for future military turbine engine testing reflect a more reasonable balance between the types of validation necessary to provide satisfactory operational weapon systems. In the past a large emphasis was placed on aerodynamic and thermodynamic aspects of the engine. Durability and reliability tended to be assigned lesser priority. This situation led to problems and failures of engines in operational service. A re-examination was conducted by the USAF of the type and methods associated with qualification of military gas turbine engines. During this examination it became evident that re-emphasis on the durability aspects of the engine was necessary.

Controlled Terms: AERODYNAMICS / *AIRCRAFT ENGINES / *AIRCRAFT RELIABILITY / *COMPONENT RELIABILITY/ *ENGINE TESTS / *FLIGHT TESTS / *GAS TURBINE ENGINES / PERFORMANCE TESTS / TEST FACILITIES / THERMODYNAMICS / *TURBINE ENGINES / WEAPON SYSTEMS

8. 80N15125
QUIET CLEAN SHORT-HAUL EXPERIMENTAL ENGINE (QCSEE) OVER-THE-WING (OTW) PROPULSION SYSTEM TEST REPORT. Volume 1: Summary report
General Electric Co., Cincinnati, Ohio.
NASA-CR-13523; R77AEG473-Vol-1 NAS3-18021 Advanced Engineering and Technology Programs Dept. 67 p.

Sea level, static, ground testing of the over-the-wing engine and boilerplate nacelle components was performed. The equipment tested and the test facility are described. Summaries of the instrumentations, the chronological history of the tests, and the test results are presented.

Controlled Terms: BOILER PLATE / *ENGINE DESIGN / *ENGINE TESTS / NACELLES / *PROPULSION SYSTEM PERFORMANCE / *QUIET ENGINE PROGRAM / TEST FACILITIES / TURBOFAN ENGINES

9. 80N14147
INVESTIGATION OF NOISE HAZARDS IN THE ENGINE TEST CELL, CFB BADEN-SOELLINGEN
Forshaw, S. E.
Defence and Civil Inst. of Environmental Medicine, Downsview (Ontario).
AD-A074391; DCIEM-TR-79-X23 790600 22 p.

Although the sound pressure levels occurring in the engine test cell, CFB Baden-Soellingen, are extremely intense (137 dBA) with a J79 engine running at military power, the attenuation provided by Canadian Forces standard-issue earmuffs is sufficient to reduce the noise at operators' ears to more tolerable levels (108 dBA). Moreover, the noise doses sustained during engine check-outs permit average work periods of up to 49 minutes per day in the test cell with engines running.

Controlled Terms: *ENGINE NOISE / *ENGINE TESTS / *HAZARDS / *HUMAN TOLERANCES / NOISE INTENSITY / NOISE MEASUREMENT / NOISE TOLERANCE / SOUND PRESSURE / *TEST CHAMBERS

10. 80A47413
GENERALIZED APPROACH TO AIRCRAFT GAS TURBINE ENGINE EQUIVALENT TEST REGIME DETERMINATION
Akhmedzianov, A. M.; Gishvarov, A. S.; Liberman, V. E.
(Aviatsionnaia Tekhnika, vol. 22, no. 3, 1979, p. 3-8.)
Soviet Aeronautics, vol. 22, no. 3, 1979, p. 1-5. Translation. 8 refs.

A method for determining equivalent regimes in the accelerated life testing of gas turbine engines is presented. The equivalent regime assures the proportional simultaneous wear-out of all the basic components of the engine. An algorithm for the determination of the optimal equivalent regime is presented along with a numerical example.

Controlled Terms: *ACCELERATED LIFE TESTS / *AIRCRAFT ENGINES / COMPONENT RELIABILITY / *ENGINE PARTS / *ENGINE TESTS / FAILURE ANALYSIS / *GAS TURBINE ENGINES / MATHEMATICAL MODELS / RELIABILITY ANALYSIS / SERVICE LIFE

11. 80A38941
A QUICK LOOK AT CURRENT RESULTS OF ACCELERATED MISSION TESTS FOR GAS TURBINE ENGINES
Jodice, R. J.; Taylor, W. R.
AIAA Paper 80-1155; AIAA, SAE, and ASME, Joint Propulsion Conference, 16th, Hartford, Conn., June 30-July 2, 1980, AIAA 6 p.

Mission related test cycles for gas turbine engines, called accelerated mission tests (AMT), are described. This concept is used in addressing engine qualification, overhaul limits, correlation with life analysis, evaluation of repair procedures, and validation of redesigned components. Test results for a TF41 engine, A-7 aircraft, F100 engine, F-15/F-16 aircraft, and TF34 engine, A-10 aircraft are presented.

Controlled Terms: A-10 AIRCRAFT / A-7 AIRCRAFT / *ACCELERATED LIFE TESTS / CYCLIC LOADS / ENGINE PARTS / *ENGINE TESTS / F-100 AIRCRAFT / F-15 AIRCRAFT / F-16 AIRCRAFT / *FATIGUE TESTS / *FLIGHT SIMULATION / *GAS TURBINE ENGINES / *GROUND TESTS / MAINTENANCE / MISSION PLANNING / *PERFORMANCE TESTS / SERVICE LIFE / TF-34 ENGINE

12. 80A38651
QCSEE UTW ENGINE POWERED-LIFT ACOUSTIC PERFORMANCE QUIET CLEAN SHORT-HAUL EXPERIMENTAL ENGINE UNDER THE WING
Loeffler, I. J.; Samanich, N. E.; Bloomer, H. E.
National Aeronautics and Space Administration. Lewis Research Center, Cleveland, Ohio. (ND315753)
AIAA Paper 80-1065 American Institute of Aeronautics and Astronautics, Aeroacoustics Conference, 6th, Hartford, Conn., June 4-6, 1980, 34 p. 17 refs.

Powered-lift acoustic tests of a quiet clean short-haul experimental engine (QCSEE) under-the-wing (UTW) engine are described. Engine and wing configurations are outlined, along with instrumentation and test facilities. The results of these tests are reported. In addition, the UTW engine powered-lift performance is compared with that of the previously tested QCSEE over-the-wing (OTW) engine.

Controlled Terms: *AIRCRAFT ENGINES / ENGINE DESIGN / ENGINE NOISE / *ENGINE TESTS / GROUND TESTS / *JET AIRCRAFT NOISE / *POWERED LIFT AIRCRAFT / *PROPULSION SYSTEM PERFORMANCE / *QUIET ENGINE PROGRAM / *SHORT HAUL AIRCRAFT / STATIC TESTS / TEST FACILITIES / WING FLAPS / WING PROFILES

13. 79A40488
A SUMMARY OF NASA/AIR FORCE FULL SCALE ENGINE RESEARCH PROGRAMS USING THE F100 ENGINE
Deskin, W. J.; Hurrell, H. G.
Pratt and Whitney Aircraft Group, West Palm Beach, Fla.
AIAA Paper 79-1308; AIAA, SAE and ASME, Joint Propulsion Conference, 15th, Las Vegas, Nev., June 18-20, 1979, AIAA AA(United Technologies Corp., Government Products Div., West Palm Beach, Fla.) 14 p. 20 refs.

This paper summarizes a joint NASA/Air Force Full Scale Engine Research (FSER) program conducted with the F100 engine during the period 1974 through 1977. The program mechanism is described and the F100 test vehicles utilized are illustrated. Technology items which have been addressed in the areas of swirl augmentation, flutter phenomenon, advanced electronic control logic theory, strain gage technology, and distortion sensitivity are identified and the associated test programs conducted at the NASA-Lewis Research Center are described. Results presented show that the FSER approach, which utilizes existing state-of-the-art engine hardware to evaluate advanced technology concepts and problem areas, can contribute a significant data base for future system applications. Aerodynamic phenomena previously not considered by current design systems have been identified and incorporated into current industry design tools.

Controlled Terms: AIRCRAFT ENGINES / COMBUSTION STABILITY / ELECTRONIC CONTROL / *ENGINE TESTS / *FLUTTER ANALYSIS / *FULL SCALE TESTS / PERFORMANCE TESTS / *RESEARCH AND DEVELOPMENT / STRAIN GAGES / STRUCTURAL DESIGN CRITERIA / STRUCTURAL STABILITY / TEST EQUIPMENT / *THRUST AUGMENTATION / *TURBOFAN ENGINES / TURBOFANS / TURBOJET ENGINE CONTROL / TURBOMACHINE BLADES

14. 79A25879
REQUIREMENTS AND CONSTRAINTS IN THE DEVELOPMENT AND QUALIFICATION OF GAS TURBINE ENGINES FOR THE NAVY
Dell, M. E.; Mead, M. D.
SAE Paper 780994 Society of Automotive Engineers, Aerospace Meeting, San Diego, Calif., Nov. 27-30, 1978, 11 p.

An improved approach to the development and qualification of aircraft turbine engines has been developed by the Navy. The approach places emphasis on durability testing throughout the engine development program. This testing is intended to assure that structural requirements have been achieved upon the introduction of new engines into service. The approach utilizes three different types of durability tests each of which is intended to address a separate aspect of the overall durability problem.

Controlled Terms: ACCELERATED LIFE TESTS / *AIRCRAFT ENGINES / AIRCRAFT RELIABILITY / CONSTRAINTS / ENGINE DESIGN / *ENGINE TESTS / FATIGUE TESTS / *GAS TURBINE ENGINES / LIFE CYCLE COSTS / *NAVY / QUALIFICATIONS / *RESEARCH AND DEVELOPMENT / *SERVICE LIFE

15. 79A25877
THE APPLICATION OF A DESIGN VERIFICATION SYSTEM AND ACCELERATED MISSION TESTING TO GAS TURBINE ENGINE DEVELOPMENT
McDonnell, B. J.
SAE Paper 780991 Society of Automotive Engineers, Aerospace Meeting, San Diego, Calif., Nov. 27-30, 1978, 13 p.

Advanced techniques for the design and development of high technology gas turbine engines are discussed, considering the improved Design Verification System (DVS) and the Accelerated Mission Test (AMT) concept. The first technique, originally developed by NASA for use in the space programs, provides the designer of a gas turbine engine with feedback data showing the relationship between his prediction and the actuals through two advanced tools: the computer analytical prediction systems, and the high technology instrumentation. Sputtered sensor, optical clearance vibration, fiber optics, and engine radiography techniques are employed in the instrumentation device. While the DVS verifies that the basic design is founded on sound assumptions, the AMT exposes the design to the damaging portions of the mission duty cycle to prove by test that the hardware will operate satisfactorily for its predicted life under flight operation conditions. The techniques are being applied to current and advanced engine programs with good success.

Controlled Terms: *ACCELERATED LIFE TESTS / *ENGINE DESIGN / ENGINE TESTING LABORATORIES / EXPERIMENTAL DESIGN / *GAS TURBINE ENGINES / NASA PROGRAMS / TEST EQUIPMENT / TIME RESPONSE

16. 79A10813
PROPULSION TEST FACILITIES TECHNICAL CAPABILITIES AND INTERNATIONAL USE
Kamchi, J. S.; Compitello, F. E.
ASME Paper 78-GT-184 American Society of Mechanical Engineers, Gas Turbine Conference and Products Show, London, England, Apr. 9-13, 1978, AB(USAF, Washington, D.C.) 8 p. 15 refs.

The requirements for additional test facilities for propulsion systems in the U.S. are identified in connection with the National Aeronautical Facilities Program (NAFP). The status of NAFP is examined and a description of the NAFP capabilities is presented. Attention is given to the National Transonic Facility, the Ames tunnel, the Turbine Engine Load Simulator, an aircraft turbine engine compressor test facility, a fuels and lubricants laboratory, and test facilities in the UK, France, Holland, and Germany. It is pointed out that there is a need for government and industry to support the facility investment necessary to make progress in aerospace technology and then to schedule as many test programs as possible in the facility.

Controlled Terms: CONTROL SIMULATION / *ENGINE TESTS / FLIGHT SIMULATORS / FUEL CONTROL / *GAS TURBINE ENGINES / LOAD TESTS / *PROPULSION SYSTEM PERFORMANCE / *TEST FACILITIES / TRANSONIC WIND TUNNELS / *WIND TUNNEL TESTS

17. 78A49731
USE OF A FIELD BENCH FOR TESTING TURBOJET ENGINES
Utilizzazione di un banco campale per la prova di turbomotori
Russo, A.; Colantonio, A.; Torella, G.
Associazione Italiana di Aeronautica e Astronautica, Congresso Nazionale, 4th, Milan, Italy, Sept. 19-23, 1977, Paper. In Italian. 48 p. 7 refs.

The paper describes the use of a field test bench for taking measurements of the thermodynamic cycle of aircraft turbojet engines. The guiding concept in selecting the instrumentation was to use a minimum of sensors without sacrificing measurement accuracy and reliability. Two attached sensors were used, consisting of two thermocouples, of which one furnished data on the static temperature downstream of the compressor and the second measured the static temperature downstream of the turbine. The test bench, sensor, and other instrumentation are described, and the method of determining the cycle from the measurements is explained.

Controlled Terms: AIRCRAFT ENGINES / *ENGINE MONITORING INSTRUMENTS / *ENGINE TESTS / FUEL CONSUMPTION / J-79 ENGINE / PROPULSION SYSTEM PERFORMANCE / *TEST STANDS / THERMOCOUPLES / *THERMODYNAMIC CYCLES / THERMODYNAMIC EFFICIENCY / THRUST / *TURBOJET ENGINES

18. 78A41507
AIRCRAFT ENGINE DESIGN AND DEVELOPMENT THROUGH LESSONS LEARNED
Koff, B. L.
(Israel Conference on Mechanical Engineering, 11th, Haifa, Israel, July 11, 12, 1977.) Israel Journal of Technology, Vol. 15, no. 4-5, 1977, p. 139-152.

The article surveys the major aspects of aircraft engine design noting tradeoff studies relative to the design configuration and aircraft system requirements. The details of design analysis are considered with reference to the theoretical stage (involving finite element analyses, vibration analyses, and three-dimensional finite element models), the experimental stage, and evaluations of material behavior. The test and evaluation program is discussed including engine cyclic endurance, instrumentation and measurement, engine unbalance testing, and process-quality controls.

Controlled Terms: *AIRCRAFT ENGINES / *DESIGN ANALYSIS / *ENGINE DESIGN / ENGINE TESTS / GAS TURBINE ENGINES / SERVICE LIFE / STRUCTURAL VIBRATION / TECHNOLOGY ASSESSMENT / TEST EQUIPMENT / *TRADEOFFS

19. 77A43619
EQUIVALENT TESTING OF GAS TURBINE ENGINES - (RUSSIAN BOOK)
Ekvivalentnye ispytaniia gazoturbinnykh dvigatelei
Kuznetsov, N. D.; Tseitlin, V. I.
Moscow, Izdatel'stvo Mashinostroenie, 1976. In Russian. 216 p. 73 refs.

The problem of estimating and increasing the service life of gas turbine engines is the subject of this book. The relevant thermomechanical properties of engine materials are studied, and methods of measuring, predicting, and increasing the service life of individual engine components are examined. These investigations serve as a basis for planning programs of equivalent accelerated tests of gas turbine engines for service life.

Controlled Terms: *ACCELERATED LIFE TESTS / ENGINE DESIGN / *ENGINE TESTS / FATIGUE LIFE / *GAS TURBINE ENGINES / MECHANICAL PROPERTIES / QUALITY CONTROL / RELIABILITY ENGINEERING / *SERVICE LIFE

20. 77A38625
ACCELERATED MISSION TESTING OF GAS TURBINE ENGINES
Taylor, W. R.; Ogg, J. S.
AIAA Paper 77-992 American Institute of Aeronautics and Astronautics and Society of Automotive Engineers, Propulsion Conference, 13th, Orlando, Fla., July 11-13, 1977, AIAA 6 p.

Commercial and military aircraft engines are designed to meet specific usage requirements. In the past, verification of these designs was based on the successful completion of a 'model' endurance test. The 'model' test was a yardstick type test and was not specifically designed to simulate actual usage. Flight experience has shown this type of qualification testing is not representative of real usage. Today, new development engines are being tested to accelerated mission test cycles. These test cycles are designed to include all significant engine excursions and time at high power conditions. In this paper, the philosophy and methodology of mission related testing of gas turbine engines will be discussed. The primary vehicle chosen for portraying this approach is the A-10/TF34-GE-100.

Controlled Terms: *ACCELERATED LIFE TESTS / *AIRCRAFT ENGINES / CYCLIC LOADS / *ENGINE TESTS / FAILURE ANALYSIS / FATIGUE TESTS / FLIGHT SIMULATION / *GAS TURBINE ENGINES / GROUND TESTS / *TF-34 ENGINE

21. 77A38593
DEVELOPMENT OF A NATIONAL COMPRESSOR RESEARCH FACILITY
Mitchell, W. H.; Martin, R. J.; Ostdiek, F. R.; Rivir, R. B.; Shahady, P. A.
AIAA Paper 77-911 American Institute of Aeronautics and Astronautics and Society of Automotive Engineers, Propulsion Conference, 13th, Orlando, Fla., July 11-13, 1977, AIAA 12 p. 11 refs.

This paper briefly describes the design and expected capability of a national compressor research facility being built at Wright-Patterson AFB including some of the analytical and experimental design evaluation techniques used during the facility development. The paper concentrates on three areas - the development of a digital model to simulate facility operation, an analytical and experimental study of inlet flow quality, and an analysis of facility noise generation and control. The paper clearly shows the strong role that analytical and experimental modelling plays in the design and development of a major test facility.

Controlled Terms: AIRCRAFT ENGINES / *COMPRESSORS / DIGITAL SIMULATION / ENGINE NOISE / *ENGINE TESTING LABORATORIES / NOISE REDUCTION / *RESEARCH FACILITIES / *TEST FACILITIES / TURBINE ENGINES

22. 75A12332
OPTIMIZATION OF AUTOMATED STATIC TESTS OF GAS TURBINE ENGINES - (RUSSIAN BOOK)
Kozhevnikov, IU. V.; Bikchantaev, M. KH.; Shershukov, V. D.; Adgamov, R. I.
Moscow, Izdatel'stvo Mashinostroenie, 1974. 104 p. In Russian. 21 refs.

Controlled Terms: *AIRCRAFT ENGINES / ALGORITHMS / *AUTOMATIC TEST EQUIPMENT / CONTROL SIMULATION / ENGINE CONTROL / ENGINE MONITORING INSTRUMENTS / *ENGINE TESTS / *GAS TURBINE ENGINES / LINEAR PROGRAMMING / MATHEMATICAL MODELS / OPTIMAL CONTROL / *OPTIMIZATION / QUADRATIC PROGRAMMING / REGRESSION ANALYSIS / *STATIC TESTS

23. 73A15708
TESTING OF JET ENGINES (RUSSIAN BOOK ON JET ENGINES TESTING COVERING TESTS IN RESEARCH AND DEVELOPMENT, DESIGN, PRODUCTION AND MAINTENANCE, TEST LABORATORIES AND STANDS AND AUTOMATION)
Skubachevskii, L. S.
Moscow, Izdatel'stvo Mashinostroenie, 1972. 228 p. In Russian. 31 refs.

Controlled Terms: AIRCRAFT ENGINES / *AUTOMATIC TEST EQUIPMENT / DATA PROCESSING / ENGINE DESIGN / *ENGINE TESTING LABORATORIES / FUEL TESTS / *JET ENGINES / PRODUCTION ENGINEERING / *RESEARCH AND DEVELOPMENT / SAFETY MANAGEMENT / TEST STANDS

2. TEST FACILITY DESIGN

24. 83A38105
THE COANDA/REFRACTION CONCEPT FOR GAS TURBINE ENGINE TEST CELL NOISE SUPPRESSION
SAE AIR 1813 SAE Aerospace Information Report, June 30, 1982, 22 p. 5 refs.

A Coanda/refraction system for suppressing gas turbine engine exhaust noise in ground run-up test cells systems is described. The overall noise characteristics of test cells were determined to be dependent on the contributions from the engine inlet, chamber walls, and the exhaust section. The Coanda effect was exploited in terms of placing walls of a channel a short distance downstream from the exiting jet. The step encouraged formation of trapped vortices between the jet and the walls, and the presence of the walls caused a lowered pressure gradient which caused the jet to move toward the walls in the absence of access to the full ambient atmosphere. Steel was selected as the structural material, with inner and outer walls isolated by neoprene. The exhaust was directed upward, and an outside hush-house enclosure ensured that fracted noise in the channel was damped within the room.

Controlled Terms: *COANDA EFFECT / EJECTORS / *ENGINE NOISE / *ENGINE TESTS / *GAS TURBINE ENGINES / *JET EXHAUST / *NOISE REDUCTION / SCALE MODELS

25. 83A22158
COMPACT INSTALLATION FOR TESTING VECTORED-THRUST ENGINES
Cunningham, W. H.; Boytos, J. F.
Journal of Aircraft, vol. 20, Mar. 1983, p. 229-235. 7 p.

Controlled Terms: *AIRCRAFT ENGINES / CASCADE FLOW / ENGINE DESIGN / *ENGINE TESTS / FLOW CHARACTERISTICS / *GROUND TESTS / HARRIER AIRCRAFT / MACH NUMBER / PROPULSION SYSTEM PERFORMANCE / REYNOLDS NUMBER / SCALE MODELS / SUBSONIC FLOW / *TEST FACILITIES / *THRUST VECTOR CONTROL / TRANSIENT LOADS / *V/STOL AIRCRAFT / VANES

26. 83N30799
AN APPLICATION OF TUNED MASS DAMPERS TO THE SUPPRESSION OF SEVERE VIBRATION IN THE ROOF OF AN AIRCRAFT ENGINE TEST CELL
Goldberg, J. L.; Clark, N. H.; Meldrum, B. H.
Commonwealth Scientific and Industrial Research Organization, Sydney (Australia).
Div. of Applied Physics. In Shock and Vibration Inform. Center. The Shock and Vibration Buil., No. 50., Part 4 p 59-68 10 p.

Tuned mass dampers were applied to suppress severe vibration in the concrete roof panels of a building used for testing constant speed turbopropeller aircraft engines. A basis for design of the dampers is described. The size and number of absorber masses and the characteristics of the spring required to effectively suppress the particular mode of the panel are determined from calculations of the model energy using experimentally measured data. The procedure is illustrated by examining the response of the slab situated above the propeller and subjected to the strongest excitation. The untreated slab, of mass estimated to be in excess of 10 tons between wall supports, vibrates with a peak velocity amplitude of 24 mm/sec in a (3.1) mode. When treated with two absorbers of total mass 470 kg, the velocity amplitude is reduced to a safe value of 4 mm/sec in the worst region of the slab. The relevance of this reduction in satisfying vibration safety criteria is discussed.

Controlled Terms: CONCRETE STRUCTURES / ENERGY TRANSFER / *ENGINE TESTING LABORATORIES / *PANELS / PRESSURE DISTRIBUTION / *ROOFS / SLABS / SPRINGS (ELASTIC) /*STRUCTURAL VIBRATION / *VIBRATION ISOLATORS / VIBRATION SIMULATORS

27. 82A37712
CURRENT TECHNIQUES FOR JET ENGINE TEST CELL MODELING
Freuler, R. J.; Dickman, R. A.
AIAA Paper 82-1272 AIAA, SAE, and ASME, Joint Propulsion Conference, 18th, Cleveland, OH, June 21-23, 1982, AIAA 16 p.

A model test program to demonstrate acceptable aerodynamic performance for a jet engine test cell with a 26 ft by 26 ft cross section is described. Utilizing a 1/17.6 scale plexiglass model of the full-scale jet engine test cell and a modified turbine powered simulator, a technique is developed in conjunction with an online data acquisition system (outlined in a block diagram) by which a maximum amount of test information can be acquired, processed, and presented to the jet cell model test engineer in a manner responsive enough to permit the 'immediate' analysis of a test point. A matrix of inlet/cell/exhaust geometries is model tested to demonstrate their interaction on the test cell system aerodynamics. This model test demonstrates acceptable test cell aerodynamics for a 26 ft by 26 ft cell geometry with a three to six inch water inlet pressure drop and a cell bypass ratio greater than 1. Specifically: no vortices are formed in the simulated engine bellmouth, the front cell velocity distortion is less than 0.20, the tip circumferential inlet distortion is less than 0.5% and the tip radial distortion is less than 0.25%. The axial pressure gradients as measured on cell walls and the simulated engine fan cowling are well below 0.5 inches of water, which corresponds to less than 0.1% correction to measured thrust due to base pressure differences.

Controlled Terms: *AERODYNAMIC CHARACTERISTICS / *AIRCRAFT MODELS / BYPASS RATIO / COMPUTER PROGRAMS / CROSS FLOW / ENGINE INLETS / *ENGINE TESTS / *FLOW CHARACTERISTICS / FLOW DISTORTION / FLOW MEASUREMENT / FLOW VISUALIZATION / *JET ENGINES / *TEST FACILITIES / TURBINE ENGINES / VORTICES

28. 82N33397
PREDICTIVE MODEL FOR JET ENGINE TEST CELL OPACITY
Final Report, 1 Jul. 1980 - 30 Sep. 1981
Lewandowski, G. A.
New Jersey Inst. of Tech., Newark.
AD-A117585; AFESC/ESL-TR-81-46; F08635-80-C-0222; AF PROJ. 1900 Dept. of Chemical Engineering. 74 p.
Tyndall AFB, Fla. Air Force Engineering Sciences Center

A computer program (written in FORTRAN for a CDC 6600) was developed to predict the plume opacity of jet engine test cells. The data input required for the model includes: the particle density, concentration, and size distribution in the exhaust gas, and the effective stack diameter. Previous data obtained for J-57 engines were used to test the model, and the difference between the theoretical and measured transmittance was generally within one percent. The program also predicts the theoretical effect of using electrostatic precipitators or venturi scrubbers to treat the exhaust emissions. These predictions indicate that control devices larger than the test cells would have to be installed to even achieve a minimal effect on the observed visibility.

Controlled Terms: AIRCRAFT MODELS / BAFFLES / COMPUTATION / *COMPUTER PROGRAMS / *EMISSION / *EXHAUST GASES / FLIGHT SIMULATION / FORTRAN / *JET ENGINES / LIGHT SCATTERING / *PLUMES / PREDICTIONS / *ROCKET EXHAUST / *SCRUBBERS / *SOOT / SPECIFICATIONS

29. 82N27326
FIELD TEST OF AN IN STACK DIFFUSION CLASSIFIER ON AN AIRCRAFT ENGINE TEST CELL
Final Report, Jun - Dec. 1980
Lundgren, D. A.; Hausknecht, B. J.
Florida Univ., Gainesville.
AD-A113811; AFESC/ESL-TR-81-21 EPA-R-805762-02-2; AF PROJ. 1900 Dept. of Environmental Engineering Sciences. 40 p. Tyndall AFB, Fla. Air Force Engineering and Services Center

An in-stack diffusion classifier was field tested at Tyndall Air Force Base, Florida. Particle size distribution measurements were made on the exhaust stream from the engine test cell while running a J75-P17 jet engine. Samples were collected at the test cell exhaust plane using a University of Washington in stack cascade impactor followed, in series, by an in stack diffusion classifier being developed at University of Florida. In addition, total particulate samples were obtained using absolute filters to determine particulate mass concentration in the exhaust gases. Opacity reading of the plume were also taken during sampling. The procedures to collect significant data and the general problems encountered to generate a reasonable estimate of jet exhaust aerosol size distribution using a diffusion classifier are described in this report.

Controlled Terms: AEROSOLS / CASCADE WIND TUNNELS / *EXHAUST EMISSION / EXHAUST GASES / *JET ENGINES / *PARTICLE SIZE DISTRIBUTION / PARTICULATE SAMPLING / *PLUMES / *TEST EQUIPMENT / TEST FACILITIES

30. 82A18727
REDUCTION OF THE ACOUSTIC ENVIRONMENT IN AN F100-PW-100 ENGINE TEST CELL
Miller, V.R.
In: Noise-Con 81; Proceedings of the National Conference on Noise Control Engineering, Raleigh, NC, June 8-10, 1981. (A82-18726 06-71) Poughkeepsie, NY, Noise Control Foundation, 1981, p. 257-260. 4 p. 5 refs.

It is found that adding the acoustic treatment to the modification of the ejector tube lowers the acoustic environment in the test cell. The measured acoustic levels after modifications are below the design levels for engine structures as close as 40 inches ahead of the engine exhaust plane for maximum afterburner for the aft ejector tube position (AETP) and standard ejector tube position (SETP) configurations. The acoustic environment in the modified test cell is found to be lowest when the ejector tube is in the aft position (AETP). The measured acoustic levels exceed the design levels for engine structure with engine operation at the forward ejector tube position (FETP) configuration at maximum afterburner.

Controlled Terms: *AIRCRAFT ENGINES / *AIRCRAFT NOISE / DATA REDUCTION / *ENGINE TESTS / *NOISE REDUCTION / NOISE SPECTRA / TEST FACILITIES

31 82N18223
FURTHER DEVELOPMENT OF THE TEST CONCEPT OF THE ALPHA JET ENGINE LARZAC 04
Weiterentwicklung des pruefkonzeptes fuer das^alpha-jet-triebwerk larzac 04
Lerche, E.
Vereinigte Flugtechnische Werke-Fokker G.m.b.H., Bremen (West Germany).
Presented at Seminars Prueftech, und Pruefstandstech., Hannover, 3 Apr. 1981 33 p.

The test stand for the LARZAC 04 jet unit for the Alpha jet aircraft was developed. The test stand is outlined, and equipment extension, and a maintenance procedure for the driving system are presented.

Controlled Terms: *AIRCRAFT ENGINES / ALPHA JET AIRCRAFT / ENGINE TESTS / ERROR ANALYSIS / *GROUND SUPPORT EQUIPMENT / *JET AIRCRAFT / *JET PROPULSION / PRELAUNCH TESTS / TEST FACILITIES / *TEST STANDS / THERMODYNAMIC PROPERTIES

32. 81A40966
TELS - A FACILITY TO OBSERVE THE EFFECT OF SIMULATED FLIGHT MANEUVER LOADS ON TURBINE ENGINES
Hagford, D. E.; Hewgley, H.E.
AIAA Paper 81-1591 AIAA, SAE, and ASME, Joint Propulsion Conference, 17th, Colorado Springs, CO, July 27-29, 1981, AIAA 9 p. 5 refs.

The current status of the Turbine Engine Loads Simulator (TELS) designed for installation at the USAF/AEDC is described. TELS will be a large centrifuge test facility capable of simulating the flight maneuvering loads (both inertial and gyroscopic) on operation full-scale turbine engines. The loads to the test engines will be generated by rotating the centrifuge at rates up to 33 rpm with the axis of the test engine positioned at radii up to 40 feet and at various angles to the centrifuge plane of rotation. The combination of radial distance and centrifuge rpm will establish the inertial loadings on the test engine while the combination of rpm and angle between the test engine axis and the centrifuge plane of rotation will control the gyroscopic loads.

Controlled Terms: *AIRCRAFT MANEUVERS / *CENTRIFUGING STRESS / COST REDUCTION / DATA ACQUISITION / *ENGINE TESTS / *FLIGHT SIMULATION / FUEL CONSUMPTION / FUEL SYSTEMS / LOAD TESTS / MAINTENANCE / RESEARCH AND DEVELOPMENT / *TEST FACILITIES / *TURBINE ENGINES

33. 81A40967
A COMPACT INSTALLATION FOR TESTING VECTORED-THRUST ENGINES
Cunningham, W. H.; Boytos, J. F.
AIAA Paper 81-1592 AIAA, SAE, and ASME, Joint Propulsion Conference, 17th, Colorado Springs, CO, July 27-29, 1981, AIAA 10 p.

An installation has been built to test the 'Pegasus' engine in its vectored-thrust mode, in a conventional enclosed sea-level test cell, in response to the Navy's requirement for test facilities for V/STOL propulsion systems. Its main features are: four vane cascades, whose design has some unique characteristics; and vertical and slant thrust measurement capability. The major criteria for the installation were met; effects on engine performance were minimal, and engine steady-state and transient operation was satisfactory from idle through maximum power. The overall performance of cascade turning vanes operating at high subsonic Mach numbers and high Reynolds numbers was also investigated.

Controlled Terms: *AIRCRAFT ENGINES / CASCADE FLOW / ENGINE DESIGN / *ENGINE TESTS / FLOW CHARACTERISTICS / *GROUND TESTS / HARRIER AIRCRAFT /MACH NUMBER / PROPULSION SYSTEM PERFORMANCE / REYNOLDS NUMBER / SCALE MODELS / SUBSONIC FLOW / *TEST FACILITIES / *THRUST VECTOR CONTROL / TRANSIENT LOADS / *V/STOL AIRCRAFT / VANES

34. 81A40900
NAPC GYROSCOPIC MOMENT TEST FACILITY
Scott, H. C.
AIAA Paper 81-1480 AIAA, SAE, and ASME, Joint Propulsion Conference, 17th, Colorado Springs, CO, July 27-29, 1981, AIAA 7 p.

The design features and operational capabilities and procedures of the Naval Air Propulsion Center (NAPC) gyroscopic moment test facility are described. The device is able to withstand engine thrust of up to 50,000 lbs, a gyroscopic load of 45,000,000 and a rotational speed of up to 3.6 radians/sec. Rig acceleration and deceleration rates are 0.22 to 0.63 radians/sec squared and 0.24 to 0.47 radians/sec squared, respectively. The maximum engine diameter accommodated is nine feet, and the maximum live load 25,000 lbs. The device determines the ability of engines to operate satisfactorily under imposed gyroscopic moments during flight maneuvers, and constitutes a viable alternative to the running of a complex flight test program.

Controlled Terms: *AIRCRAFT ENGINES / ENGINE MONITORING INSTRUMENTS / *ENGINE TESTS / EQUIPMENT SPECIFICATIONS / *GYROSCOPIC STABILITY / *MILITARY AIRCRAFT / NAVY / ROTATING ENVIRONMENTS / *TEST FACILITIES / TEST STANDS

35. 81A37796
CONTROL OF PARTICULATE EMISSIONS FROM TURBINE ENGINE TEST CELLS BY COOLING WATER INJECTION
Stockham, J. D.; Lannis, M. D.; MacNaughton, M. G.; Tarquinio, J. J.
Air Pollution Control Association, Journal, vol. 31, June 1981, p. 675-678. 4 p.

Water injected into test cells for structural cooling removes a substantial portion of turbine engine exhaust particles that cause test cells to violate opacity regulations. Tests on a number three test cell in a J75-P17 aircraft turbine engine revealed that the percentage of particle removal increased with flow rate. Removal efficiencies ranged from 28% at a flow rate of 1900 L/min to 55% at 3700 L/min. A recommended 3028 L/min (to avoid droplet fallout at too high flow rates) would remove 50% of the solids at 95% of maximum RPM and have a higher removal percentage at lower engine RPM. The water that would normally drain from the test cell was analyzed chemically and microscopically to differentiate between engine exhaust particles and solids present in the injected cooling water, and it was found that the injected water also removed hydrocarbons from the exhaust gases.

Controlled Terms: *AIRCRAFT ENGINES / ENGINE CONTROL / *ENGINE TESTS / *EXHAUST EMISSION / FLOW VELOCITY / HYDROCARBONS / *LIQUID COOLING / *PARTICULATE SAMPLING / *POLLUTION CONTROL / *TURBINE ENGINES / WATER INJECTION

36. 81A34157
A REVIEW OF THE INSTALLATION, PERFORMANCE AND ECONOMIC ASPECTS OF A HIGH ALTITUDE FACILITY FOR SMALL GAS TURBINES
Koury, G.
SAE Paper 80-1121 Society of Automotive Engineers, Aerospace Congress and Exposition, Los Angeles, Calif., Oct. 13-16, 1980, 9 p.

A new Canadian facility capable of simulating high altitude conditions (up to 40,000 ft) for testing the performance of small gas turbine engines is discussed in terms of technical and economic advantages. The modification project to change an existing facility into a test cell capable for high altitude testing is described and the main control room, vacuum chamber, high precision and mechanical instruments needed to obtain pressure and temperature control are discussed. Comparing the ground level with existing flying test bed facilities, the former was seen to adapt more easily to adapt more easily to different engine models due to fewer constraints on weight and space. It is concluded that a high quality performance data can be obtained at considerably lower cost and in relatively shorter time, when testing is not exclusively done in a flying test bed, but in conjunction with the new ground facility.

Controlled Terms: *COST EFFECTIVENESS / ECONOMIC ANALYSIS / *ENGINE TESTS / ENVIRONMENT SIMULATION / *FLIGHT TESTS / *GAS TURBINE ENGINES / GROUND TESTS / *HIGH ALTITUDE TESTS / INSTALLING / PERFORMANCE TESTS / PRESSURE MEASUREMENTS / *PROPULSION SYSTEM PERFORMANCE / TEMPERATURE CONTROL / TEMPERATURE MEASUREMENT / VACUUM CHAMBERS

37. 81N18067
VALIDATION OF A TWO-DIMENSIONAL PRIMITIVE VARIABLE COMPUTER CODE FOR FLOW FIELDS IN JET ENGINE TEST CELLS
Final Report
Mallon, P. J.; Hickey, P. J; Netzer, D. W.
Naval Postgraduate School, Monterey, Calif.
AD-A094615; NPS67-80-014 Sponsored by Navy 73 p.

Pressure and velocity data were collected in a full scale jet engine test cell in order to validate the predictive accuracy of a two dimensional and axisymmetric primitive variable computer code. It was found that the model reasonably predicted the velocity profiles in the augmentor tube. Inaccuracy increased at higher engine thrust settings at positions far downstream in the augmentor tube. Predicted pressure profiles were reasonable but the magnitudes were in considerable error at high flow rates.

Controlled Terms: *COMPUTERIZED SIMULATION / DATA ACQUISITION / DATA REDUCTION / *ENGINE TESTS / FLOW VELOCITY / FULL SCALE TESTS / *JET ENGINES / *PROGRAM VERIFICATION (COMPUTERS) / TEST FIRING / VELOCITY DISTRIBUTION

38. 80N20287
AEROSOL FILTER LOADING DATA FOR A SIMULATED JET ENGINE TEST CELL AEROSOL
Final Report, Jan. - Jul. 1979
Lundgren, D. A.
Environmental Engineering Consultants, Inc., Gainesville, Fla.
AD-A078779; ESL-TR-79-28 F08637-79-M-0784; AF PROJ. 1900 44 p. Tyndall AFB, Fla.
Air Force Engineering and Services Center.

The Air Force routinely tests turbine engines in fixed test cells, some of which have been cited by state pollution control officials for violations of opacity regulations. A previous theoretical study, CEEDO-TR-78-53, predicted that relatively low efficiency and low cost techniques could bring jet engine test cells into compliance with air pollution regulations. The system proposed included a water cooling spray and a mist eliminator followed by a medium efficiency, high velocity, throw-away type glass filter media. The most serious limitation of velocity filtration is the aerosol mass loading and the potential for rapid pressure drop build up across the filter. Since filter loading characteristics could not be theoretically predicted, the objective of this follow-on work was to experimentally test and report the filter loading characteristics of glass fiber filters for possible application to jet engine test cell exhaust plume opacity control. Two types of glass fiber media were tested: (1) two different medium efficiency pre-filter media; and (2) two different high efficiency final filter media.

Controlled Terms: *AEROSOLS / AIR POLLUTION / *ENGINE TESTING LABORATORIES / EXHAUST GASES / *FLUID FILTERS / GLASS FIBERS / *JET ENGINES / JET EXHAUST / *OPACITY / *POLLUTION CONTROL / SMOKE

39. 80N29338
FLOW QUALITY FOR TURBINE ENGINE LOADS SIMULATOR (TELS) FACILITY
Final Report, 1 Oct. 1978 - 1 Sep. 1979
Schulz, R. J.
ARO, Inc., Arnold Air Force Station, Tenn.
AD-A086084; AEDC-TR-79-83 38 p.

A study was made to define the flow quality in air inlets used to support engine testing in the proposed Turbine Engine Loads Simulator Facility (TELS). The study showed that inlets could be designed that would produce separation-free flow for the worst case of crossflow induced by TELS rotation. The severity of recirculated exhaust gas ingestion by the inlet was estimated using a finite-difference numerical simulation of the engine and its exhaust deflector. Finally, a method was devised for defining the performance of a representative engine, the Pratt and Whitney F100 engine. The possible effects of inlet flow nonuniformity on engine performance in TELS were detailed.

Controlled Terms: *COMPUTERIZED SIMULATION / ENGINE TESTS / *EXHAUST GASES / *FLOW DISTRIBUTION / *INGESTION (ENGINES) / INLET FLOW / NUMERICAL ANALYSIS / TEST FACILITIES / *TURBINE ENGINES

40. 80A23069
DESIGNING OF THE TEST UNITS FOR AIRCRAFT ENGINES (RUSSIAN BOOK)
Proektirovanie ispytatel'nykh stendov dlia aviatsionnykh dvigatelei
Pavlov, IU. I.; Shain, IU. IA.; Abramov, B. I.
Moscow, Izdatel'stvo Mashinostroenie, 1979, 152 p. 72 refs.

The book deals with designing of the test units for aircraft turbojet engines and their parts. Emphasis is placed on test modelling and modern test units which make it possible to imitate high-speed, take-off-landing, weather, and other conditions under which these engines operate.

Controlled Terms: *AIRCRAFT ENGINES / CALIBRATING / *ENGINE TESTS / ENVIRONMENT SIMULATION / FLIGHT SIMULATION / LANDING SIMULATION / NOISE REDUCTION / *TEST STANDS

41. 80N18587
CONTROL OF PARTICULATE EMISSIONS FROM TURBINE ENGINE TEST CELLS BY COOLING WATER INJECTION
Final Report, Feb - May 1979
MacNaughton, M. G.; Tarquinio, J. J.; Martone, J. A.
Air Force Engineering and Services Center, Tyndall AFB, Fla.
AD-A075947; AFESC/ESL/TR-79-19 AF PROJ. 1900 Engineering and Services Lab. 77 p.

The operation of DOD turbine engine test cells in California has been criticized by the State environmental regulatory agencies because smoke generated by some engines results in excessive opacity (visibility) of the test cell exhaust plume. Since the plume exceeds visibility standards for only a relatively small proportion of engines tested a low cost control technique which brings the test cell into compliance with opacity standards is required. This study was initiated to verify that, in addition to forming a steam plume, water used to cool the test cell walls also removes engine generated particulates and substantiates this procedure as a legitimate pollution control technique. It can be concluded from this study that water injection as practiced at McClellan AFB test cell results in significant (approx. 50% by weight) control of turbine engine particulate emissions. It is postulated that the process could be made more efficient by the use of better designed spray nozzles which would increase water droplet particle contact and inclusion of a demister to increase water removal from the exhaust.

Controlled Terms: AIR POLLUTION / *EXHAUST EMISSION / *LIQUID COOLING / PARTICLES / PLUMES / *POLLUTION CONTROL / SPRAY NOZZLES / *TEST EQUIPMENT / *TURBOJET ENGINES / WATER INJECTION

42. 80N17091
JET ENGINE CLASS C TEST CELL EXHAUST SYSTEM PHASE.
COANDA/REFRACTION NOISE SUPPRESSION CONCEPT-ADVANCED DEVELOPMENT
Technical Report, Oct. 1976 - Jan. 1977
Ballard, R.E.; Armstrong, D. L.
Boeing Co., Wichita, Kans.
AD-A075277; D3-11500-1; NAEC-92-113 N00140-76-C-1229 89 p.
Lakehurst, NJ Naval Air Engineering Center

The successfully demonstrated Coanda/refraction air-cooled exhaust noise suppressor system is applied to the Navy requirement for an effective air-cooled retrofit configuration for the class 'C' test cells (concrete enclosure). The technical approach consists of analytically sizing retrofit components to meet both acoustic and aerothermodynamic requirements and then testing at one-sixth scale using simulated afterburning engine exhaust to verify the design configuration. Model variations included exhaust stack height, exhaust stack inner flow passage configurations (straight walls and diffuser) and removal of a concrete internal partition wall. Extensive data were recorded and analyzed to identify the aerothermodynamic trends related to these configuration changes. Results present recommendations for an air-cooled Coanda exhaust noise suppression system for retrofit of Navy class 'C' test cells.

Controlled Terms: AEROTHERMODYNAMICS / *ENGINE TESTS / EXHAUST DIFFUSERS / EXHAUST NOZZLES / *EXHAUST SYSTEMS / *JET AIRCRAFT NOISE / *NOISE REDUCTION / SCALE MODELS / TEST CHAMBERS / TF-30 ENGINE

43. 79N27173
A NEW FACILITY FOR STRUCTURAL ENGINE TESTING
Swain, R. L. B.; Mitchell, J. G.
Arnold Engineering Development Center, Arnold Air Force Station, Tenn.
In AGARD Stresses, Vibrations, Struct. Integration and Eng.
Integrity (Including Aeroelasticity and Flutter) 6 p.

A test facility to simulate the maneuver environment an engine actually experiences in flight is presented. The facility and its potential benefits to the engine development process are described.

Controlled Terms: *ENGINE TESTS / FLIGHT SIMULATORS / FLIGHT TESTS / LOADS (FORCES) / PROBLEM SOLVING / STRESS ANALYSIS / *STRUCTURAL DESIGN / STRUCTURAL STRAIN / *TEST FACILITIES / TURBINE ENGINES

44. 79N21078
LOW EFFICIENCY CONTROL MEASURES FOR JET ENGINE TEST CELLS
Final Report, Apr. - Sep. 1978
Lundgren, D. A.
Gainesville, Fla.
AD-A062665; CEEDO-TR-78-53 F08637-78-M-1387 25 p.

This report summarizes the findings of low cost, relatively low efficiency emission control measures for reduction of jet engine test cell opacity to less than 20%. The recommended cost effective opacity reduction system consists of an effective water spray system; a glass fiber mist eliminator; a medium efficiency, high velocity, throw-away type glass fiber filter media; and a reduced test cell discharge area. The report discussed the following topics: control methods, opacity, scrubbers, demisters, and filters.

Controlled Terms: *AIR POLLUTION / COST EFFECTIVENESS / *EXHAUST GASES / FILTERS / GAS TURBINES / GLASS FIB''RS / *JET ENGINES / *POLLUTION CONTROL / SMOKE

45. 79N20530
PARTICLE COLLECTION BY WATER INJECTION IN TEST CELLS
Interim Report, 1 Sep - 1 Oct. 1978
Daley, P. S.; Lundgren, D. A.
Civil and Environmental Engineering Development Office, Tyndall AFB, Fla.
AD-A062154; CEEDO-TR-78-51 9 p.

This report summarizes the mechanisms by which particles may be removed when water is injected into turbine engine test cell exhaust streams. The report concludes that impaction between soot particles and droplets is the most important mechanism and that there is an optimum flow rate at which water should be injected to assure maximum removal efficiency.

Controlled Terms: AIR POLLUTION / EXHAUST GASES / FLOW VELOCITY / *GAS-LIQUID INTERACTIONS / PARTICLE EMISSION / *PARTICLES / SMOKE / *TEST CHAMBERS / TURBINE ENGINES / *WATER INJECTION

46. 79N16855
THE FEASIBILITY OF CONTROLLING TURBINE ENGINE TEST CELL PARTICULATE EMISSIONS WITH A BAGHOUSE
Final Report, Sep. 1977 - Mar. 1978
Geiger, J. R.; Daley, P. S.
Florida Univ., Gainesville
AD-A061120L; CEEDO-TR-78-24 F08637-78-M-0252 Dept. of Environmental Engineering Sciences. 79 p.

Air pollution regulations dictate that the Department of Defense attempt to control visible emissions emitted from turbine engine test cells. Previous studies have summarily dismissed baghouses as a control device because of potential size, pressure drop, explosion and fire hazard, and excessive cost. This report addresses these problems in the design of a baghouse for controlling emissions from a TF30-P100 engine.

Controlled Terms: *AIR POLLUTION / COMBUSTION ''DUCTS / *EXHAUST GASES / *POLLUTION CONTROL / SCRUBBERS / *TURBINE ENGINES

47. 79N11580
JET ENGINE TEST CELLS: EMISSIONS AND CONTROL MEASURES, PHASE 1
Final Report, 13 Aug. 1976 - 30 Sep. 1976
Blake, D. E.
Acurex Corp., Mountain View, Calif.
PB-283470/3; AEROTHERM-FR-76-218; TR-78-102; EPA-340/1-78-001A
EPA-68-01-3158 Aerotherm Div. 139 p.

The current state of the art of pollutant emission measurement and cleanup technology related to military jet engine test cells are discussed. Considerable emissions data from jet engines is available, but data from test cell stacks is sparse. An electrostatic precipitator, nucleation scrubber, fuel additives, thermal converter, and fuel atomization improvement were evaluated. Several methods are quite effective in reducing test cell emissions. Fuel additives are effective in reducing test cell plume opacity. Capital and operating cost data on these methods are presented.

Controlled Terms: AIR POLLUTION / ELECTROSTATIC PRECIPITATORS / *EMISSION / *EXHAUST GASES / *JET ENGINES / *POLLUTION CONTROL / SCRUBBERS / TECHNOLOGY ASSESSMENT / TEST CHAMBERS

48. 79N10072
JET ENGINES TEST CELLS: EMISSIONS AND CONTROL MEASURES, PHASE 2
Final Report
Kelly, J.; Chu, E.
Aerotherm Acurex Corp., Mountain View, Calif.
PB-282412/6; ACUREX/TR-78/102; EPA-340/1-78-001B; EPA-68-01-4142 158 p.

Background information is provided on the environmental aspects of uncontrolled and controlled military jet engine test cell operations. The environmental impact of these operations is considered on both a source and an air quality basis. Wet-packed scrubber, jet engine clean combustor, and ferrocene fuel-additive test cell emissions control strategies are described. Clean combustor technology and its associated cost of implementation are discussed in detail. It is estimated that for some jet engine tests, applying clean combustors can cause NOx emissions to rise above local stationary source regulations. The air quality impact of controlled jet engine test cell emissions is small.

Controlled Terms: ADDITIVES / *AIR POLLUTION / *ENVIRONMENTAL SURVEYS / FUEL COMBUSTION / JET ENGINES / *JET EXHAUST / NITROGEN OXIDES / *POLLUTION CONTROL / SCRUBBERS / TECHNOLOGY ASSESSMENT / *TEST FACILITIES

49. 78N20148
SMOKE ABATEMENT FOR DOD TEST CELLS
Final Report, 20 Nov. 1976 - 30 May 1977
Grems, B. C., III
Air Force Civil and Environmental Engineering Office, Tyndall AFB, Fla.
AD-A050223; CEEDO-TR-77-40 AF PROJ. 2103 109 p.

The Department of Defense owns and operates nearly 200 jet engine test cells. Occasionally, visible exhaust smoke is emitted from these structures. Several pollution control agencies, most notably the state of California, have expressed interest in limiting test cell smoke emissions. A review committee composed of various Air Force and Navy representatives recommended further study of fuel additives as a means of achieving this goal. They recognized additives as the most promising near term solution to the test cell smoke problem. Ferrocene appeared to be the best of existing additives. Studies were undertaken to determine the environmental impact, toxicological hazards and engine effects associated with routine ferrocene use. Four types of Navy turbine engines were tested for ten hours each using ferrocene. These tests indicated that engines suffered no harm attributable to ferrocene, but that the additive must be certified for each engine type on a individual basis. Emission measurements made during the tests showed that most pollutants are virtually unchanged in quantity and character by ferrocene use and that particulate matter is actually reduced.

Controlled Terms: AIR POLLUTION / *EXHAUST GASES / FERROCENES / JET ENGINE FUELS / *JET ENGINES / *MILITARY OPERATIONS / PARTICLE EMISSION / *SMOKE ABATEMENT / *TEST FACILITIES / TOXIC HAZARDS

50. 78N17079
EVALUATION OF THE EXTENDED USE OF FERROCENE FOR TEST CELL SMOKE ABATEMENT ENGINE AND ENVIRONMENTAL TEST RESULTS
Interim Report
Klarman, A.F.
Naval Air Propulsion Test Center, Trenton, N.J.
AD-A047659; NAPTC-PE-110 Propulsion Technology and Project Engineering Dept. 126 p.

Results of a test program to evaluate the feasibility of utilizing the smoke suppressant fuel additive, ferrocene, during post overhaul performance checks of gas turbine engines at Naval Air Rework Facilities (NARF's) and other lower level maintenance test facilities to reduce test cell exhaust smoke plumes to environmentally acceptable levels are presented. This test program was conducted on the following gas turbine engines: J52-P-6B, J57-P-10, J79-GE-8D, TF30-P-6C and TF41-A-2A.

Controlled Terms: *ADDITIVES / AIR POLLUTION / *ENGINE TESTS / *ENVIRONMENTAL TESTS / EXHAUST GASES / *FERROCENES / *GAS TURBINE ENGINES / POLLUTION CONTROL / *SMOKE ABATEMENT / TURBOFAN ENGINES / TURBOJET ENGINES

51. 78N12107
EVALUATION OF AN AUTOMATED SMOKE ABATEMENT SYSTEM FOR JET ENGINE TEST CELLS
Final Report
Klarman, A. F.
Naval Air Propulsion Test Center, Trenton, N.J.
AD-A044587; NAPTC-PE-108 Propulsion Technology and Project Engineering Dept. 28 p.

An Automated Smoke Abatement System (ASAS) which injects a smoke abatement fuel additive into the fuel system of a gas turbine engine was developed for reducing test cell exhaust stack plume opacity caused by engine operation. The ASAS contains three major components: (a) transmissometer to monitor plume opacity, (b) logic/control unit which determined if opacity exceeds the standard, and (c) variable speed pump which injects the optimum quantity of the smoke abatement additive. The difference between the plume opacity and standard, regulates the speed of the pump and quantity of additive injected. The system maintained test cell plume opacity to a visual opacity of 20 percent or less during evaluation tests at two Naval Air Rework Facilities (NARF's). It is recommended that the ASAS be used to control plume opacity from those engines compatible with smoke abatement additives.

Controlled Terms: *EXHAUST GASES / FUEL SYSTEMS / *GAS TURBINE ENGINES / POLLUTION CONTROL / *SMOKE ABATEMENT / SYSTEMS ENGINEERING

52. 78N11521
ABATEMENT OF PARTICULATE EMISSIONS AND NOISE FROM JET ENGINE TEST CELLS INCLUDING REDUCTION OF GAS FLOW WITH THE TEST AUGMENTER SCRUBBER SYSTEM
Final Report
Teller Environmental Systems, Inc., N. Y.
AD-A043255 N62467-70-C-0240 131 p.

The prototype scrubber and augmentation system designed for and operated in Black Point Test Cell Number 1 NARF-Jacksonville has abated emissions to the projected design level. The engines operated with the system were the J-79, TF-30, and J-52. Particulate emissions were reduced to the 0.002-0.005 gr/SCF level. The visible emissions fell well within the Ringleman 1/2 level after dissipation of the steam plume. No fallout was evident during operation of the system. It was further established that engine test performance was not affected by the TESI system. The scrubber system was mounted on the exhaust stack of the cell thus obviating the necessity for costly ducting and the requirement for ground utilization. The size requirement of the scrubber was reduced significantly with the use of a new augmenter design that decreased the induced air to jet exhaust flow ratio from values in the range of 2:1 to 0.4-0.6:1. This new augmenter can reduce the augmentation even further, thus providing the potential of retrofit of existing cells to accommodate engines larger than now being tested. Sound levels were reduced by the installation of the scrubber from 6-10 decibels (dBA), where the original sound level was of the order of 90-95 dBA. GRA

Controlled Terms: AIR POLLUTION / *ENGINE NOISE / NOISE REDUCTION / SCRUBBERS / *TURBOFAN ENGINES / *TURBOJET ENGINES

53. 77N18173
TEST AND EVALUATION OF A PILOT TWO-STAGE PRECIPITATOR FOR JET ENGINE TEST CELL EXHAUST GAS CLEANING
United Engineers and Constructors, Inc., Boston, Mass.
AD-A030100; N62467-74-C-0161; N00025-72-C-0037 115 p.

Findings of a study for the abatement of air pollution caused by operation of Naval jet engine test facilities, issued in August 1973, were that the use of fuel additives, the retrofit of smokeless combustors and the installation of gas cleaning equipment were potential means of controlling particulate emissions from the cells. Additives and smokeless combustors were found to require additional development leaving exhaust gas cleaning as the only technology then available for emission control. A two-stage electrostatic precipitator was recommended as the most viable alternative to a concept then being actively developed, the cross-flow wet scrubber. Due to the unique nature of the application and the high cost of full-sized equipment, it was recommended that a bench scale precipitator be tested to confirm performance and establish size parameters. Such a prototype unit was subsequently installed at Black Point test cell No. 1, Naval Air Rework Facility, Jacksonville, Florida and underwent a sequence of performance and operating tests under the supervision of UE and C. This report summarizes the results of the test program and provides data on the economics of applying a full-scale system to a jet engine test cell.

Controlled Terms: AIRPLANE PRODUCTION COSTS / *ELECTROSTATIC PRECIPITATORS / *EXHAUST GASES / FUEL CELLS / *JET ENGINES / NAVY / *POLLUTION CONTROL / SCALE MODELS

54. 77A40643
TRANSMISSOMETER MEASUREMENT OF PARTICULATE EMISSIONS FROM A JET ENGINE TEST FACILITY
Chang, D. P. Y.; Grems, B. C.
Air Pollution Control Association, Journal, vol. 27, July 1977 p. 673-675.

An optical transmissometer was assessed as a possible means of monitoring potential mass emissions in turbojet test facilities. Simultaneous cascade impactor samples and opacity measurements were used to determine the relationship between mass concentration and plume opacity. A correlation coefficient of 0.87 was found in a least squares regression analysis of total mass concentration on optical density. A better correlation coefficient was obtained when particles with diameters greater than 3 microns were excluded. However, a successful correlation of total mass emissions rate with opacity is believed to be unlikely, even for smaller engines.

Controlled Terms: *AIR POLLUTION / AIR SAMPLING / *ENGINE MONITORING INSTRUMENTS / ENGINE TESTS / EXHAUST GASES / GAS DENSITY / LEAST SQUARES METHOD / OPTICAL MEASURING INSTRUMENTS / *PARTICULATE SAMPLING / PLUMES / POLLUTION MONITORING / REGRESSION ANALYSIS / *TEST FACILITIES / *TRANSMISSOMETERS / *TURBOJET ENGINES

55. 74N27302
STANDARDIZATION OF TESTING BENCHES FOR FRENCH TEST FACILITIES
Gourgeon. P.; Badaroux, J. P.; Durollet, A.
Air Force Systems Command, Wright-Patterson AFB, Ohio.Foreign Technology Div
AD-777208 FTD-HC-23-700-74 REPT-998 Foreign Technology Div.
Transl. into English of Centre d'Essais de Propulseurs, Saclay, France, report no. 998, 1972 p 1-39.

Controlled Terms: AIRCRAFT ENGINES / *FRANCE / PRODUCTION ENGINEERING / *STANDARDIZATION / *TEST FACILITIES / TEST STANDS

56. 74N13957
TURBOJET AIRCRAFT ENGINE TEST CELL POLLUTION ABATEMENT STUDY
Final Report, Jul. - Dec. 1972
Davies, G. F.; Crow, R. H.
Braun (C. F.) and Co., Alhambra, Calif.
AD-768287 NCEL-CR-74.001 N62399-72-C-0020 96 p.

Controlled Terms: AIR FILTERS / *AIR POLLUTION / COMBUSTION PRODUCTS / *CONTROL EQUIPMENT / ELECTROSTATIC PRECIPITATORS / *EXHAUST GASES / J-79 ENGINE / *TURBOJET ENGINES

57. 73N29690
ANALYSIS OF JET ENGINE TEST CELL POLLUTION ABATEMENT METHODS
Technical Report, 21 Feb 1972 - 21 Feb. 1973 (Analysis of jet engine test cell pollution abatement methods)
Robson, F. L.; Kesten, A. S.; Lessard, R. D.
United Aircraft Corp., East Hartford, Conn.
AD-763119 AFWL-TR-73-18; F29601-72-C-0049 AF PROJ. 683M 231 p. Kirtland AFB, N. Mex.

Controlled Terms: *AIR POLLUTION / CONTAMINANTS / COST EFFECTIVENESS / *EXHAUST GASES / *JET ENGINES / NITROGEN OXIDES

58. 73A14902
INSTRUMENTATION AND MEASUREMENT FOR DETERMINATION OF EMISSIONS FROM JET ENGINES IN ALTITUDE TEST CELLS
Grissom, J. L.
AIAA Paper 72-1068; F40600-73-C-0004 American Institute of Aeronautics and Astronautics and Society of Automotive Engineers, Joint Propulsion Specialist Conference, 8th, New Orleans, La., Nov. 29 Dec. 1, 1972, AIAA 11 p. 6 refs.

Controlled Terms: AIR POLLUTION / *ALTITUDE SIMULATION / CARBON DIOXIDE / CARBON MONOXIDE / CHEMILUMINESCENCE / CONTAMINANTS / *ENGINE TESTS / FLAME IONIZATION / *GAS ANALYSIS / *GAS COMPOSITION / HYDROCARBONS / INFRARED DETECTORS / *JET EXHAUST / MICROBALANCES / NITROGEN OXIDES / PARTICULATE SAMPLING / ULTRAVIOLET ABSORPTION / WATER VAPOR

3. TEST TECHNIQUES

59. 83A47943
AUTOMATED DIAGNOSTIC SYSTEM FOR ENGINE MAINTENANCE - VIBRATION DATA EXTRACTION FROM GAS TURBINE ENGINES
Fanuele, F.; Rio, R. A.
ASME Paper 83-GT-103 American Society of Mechanical Engineers, International Gas Turbine Conference and Exhibit, 28th, Phoenix, AZ, Mar. 27-31, 1983. 4 p. USAF-supported research.

The Automated Vibration Diagnostic System (AVID) developed for the U.S. Air Force jet engine overhaul centers is described. AVID automates troubleshooting procedures for fully assembled gas turbine engines. High-frequency vibration data are extracted from existing standard instrumentation to provide input to a specialized symptom/fault matrix. This matrix is configured to analyze the incoming data and to assign a particular malfunction (or malfunctions) to a specified data set. This diagnosis is printed out to provide maintenance personnel with precise knowledge of what the problem is and how to correct it. It is noted that AVID should enable the Air Force to significantly reduce expenses at the jet engine overhaul centers.

Controlled Terms: *AIRCRAFT ENGINES / AIRCRAFT MAINTENANCE / *AUTOMATIC TEST EQUIPMENT / COMPUTER TECHNIQUES / COST EFFECTIVENESS / DATA REDUCTION / *ENGINE MONITORING INSTRUMENTS / *ENGINE TESTS / FAILURE ANALYSIS / *GAS TURBINE ENGINES / JET ENGINES / MALFUNCTIONS / TESTING TIME / *VIBRATION TESTS

60. 83A36398
DEVELOPMENT OF SIMULATED MISSION ENDURANCE TEST ACCELERATION FACTORS IN DETERMINING ENGINE COMPONENT SERVICEABILITY AND FAILURE MODE CRITICALITY
Metz, T. R.; Zimmerman, P. J.
AIAA Paper 83-1409; AIAA, SAE, and ASME, Joint Propulsion Conference, 19th, Seattle, WA, June 27-29, 1983. 6 p.

The use of Accelerated Simulated Mission Endurance Testing (ASMET) is a cost effective method of verifying engine durability in projected aircraft weapon system application. ASMET is a gas turbine engine durability test which simulates the aircraft mission in a test environment. A test acceleration methodology has been developed utilizing mission profiles and mission mix to define composite profiles which do not lose mission orientation and still accelerate the damage processes. Identifying the damage processes is critical since failure mode damage acceleration rates will differ with each failure mode. These failure mode conditions are identified from the mission profile/mission mix and retained in the composite profile, while non-damaging mission aspects are deleted. The composite profiles are then used as the ASMET cycle. The ASMET acceleration factors are then determined as a ratio of mission profile/mission mix time to test composite time.

Controlled Terms: *ACCELERATED LIFE TESTS / ENDURANCE / *ENGINE FAILURE / *ENGINE PARTS / *ENGINE TESTS / *FAILURE MODES / *GAS TURBINE ENGINES / NAVY / PERFORMANCE TESTS / WEAPON SYSTEMS

61. 83A36357
ACCELERATED SIMULATED MISSION ENDURANCE TEST OF A TURBOSHAFT ENGINE FOR MILITARY ATTACK HELICOPTER APPLICATION
Davis, S. P.
AIAA paper 83-1359 AIAA, SAE, and ASME, Joint Propulsion Conference, 19th, Seattle, WA, June 27-29, 1983. 10 p.

A test was conceived to subject a factor development test engine to simultaneous vibration and power excursions. During the period from March, 1981, through May, 1982, testing was performed on a T700-701 turboshaft engine mounted in a factory test cell. The engine and externally mounted airframe hardware were from an AH-64A helicopter. Attention is given to aspects of helicopter simulation, mission simulation, a facility description, details regarding the test method, and the test results. It was found that the accelerated simulated mission endurance test (ASMET) conducted met the objectives of demonstrating equivalent 5000 field mission hour capability of the engine and attached aircraft components.

Controlled Terms: *ACCELERATED LIFE TESTS / BEARINGS / *ENGINE TESTS / EXHAUST NOZZLES / FAILURE ANALYSIS / *HELICOPTER ENGINES / *MILITARY HELICOPTERS / *PERFORMANCE TESTS / STRUCTURAL FAILURE / *TURBINE ENGINES / VIBRATION TESTS

62. 83A36298
ACCELERATED MISSION TESTING OF THE F110 ENGINE
Castells, O. T.
AIAA Paper 83-1235 AIAA, SAE, and ASME, Joint Propulsion Conference, 19th, Seattle, WA, June 27-29, 1983. 7 p.

A summary of the new use of Accelerated Mission Testing (AMT), in the development of the F110 Engine (formerly F101 DFE), is presented. A comparison of the AMT to previous qualification tests and to actual field service is presented. This test approach has been now adopted as the official endurance qualification test for the USAF.

Controlled Terms: *ACCELERATED LIFE TESTS / *AIRCRAFT ENGINES / *ENGINE TESTS / *F-4 AIRCRAFT / LIFE (DURABILITY) / *PERFORMANCE TESTS

63. 83A36297
DETERIORATION TRENDING ENHANCES JET ENGINE HARDWARE DURABILITY ASSESSMENT AND PART MANAGEMENT
Barrett, R. J.; Harris, W. R., Jr.
AIAA Paper 83-1234; AIAA, SAE, and ASME, Joint Propulsion Conference, 19th, Seattle, WA, June 27-29, 1983. 6 p.

The exposure of a new aircraft engine to the service environment can reveal engine hardware durability limitations not evident during the development or model acceptance phase of an engine program. In connection with the recognition by the Navy of the need for an improved full-scale engine test to assure the long-range durability characteristics of the engine, a new approach for assessing engine hardware durability improvements was initiated in 1978. The approach included Accelerated Simulated Mission Endurance Test (ASMET) and fleet engine hot section hardware deterioration comparisons. Part deterioration 'trending' was initiated during ASMET engine hot section inspections in order to establish a baseline of trending data for comparison with fleet hardware. It is pointed out that jet engine hardware deterioration trending is now a proven method for enhancing long-term durability evaluation of new and improved hardware designs.

Controlled Terms: ACCELERATED LIFE TESTS / *AIRCRAFT ENGINES / *DURABILITY / *ENGINE PARTS / ENGINE TESTS / EVALUATION / *HARDWARE / *JET ENGINES / QUALITY CONTROL / TF-30 ENGINE / *TURBINE ENGINES

64. 83A36296
AIRCRAFT ENGINE INLET PRESSURE DISTORTION TESTING IN A GROUND TEST FACILITY
Anderson, R. E.
AIAA Paper 83-1233; AIAA, SAE and ASME, Joint Propulsion Conference, 19th, Seattle, WA, June 27-29, 1983 12 p. 7 refs.

At first, the problem of inlet distortion as it affected the stability of a jet engine in a high performance aircraft was either underestimated or not understood. Inlet pressure distortion phenomena can be divided into steady-state and time-variant categories. A review is provided of various methods for producing each type. Steady-state pressure distortion is the relatively constant pressure variation from the average pressure of the measurement plane. A variation from the center to the outside diameter is called radial distortion, while circumferential distortion represents variation on any concentric circle. Steady-state total pressure distortion for test purposes is generally produced by screens. Attention is given to a distortion valve, distortion screens for steady-state pressure patterns, aspects of screen design, design revisions, the measurement of steady-state distortion, time-variant distortion, and random frequency generators.

Controlled Terms: *AIRCRAFT ENGINES / *ENGINE INLETS / *ENGINE TESTS / EQUILIBRIUM FLOW / *FLOW DISTORTION / GAS TURBINE ENGINES / GROUND TESTS / *INLET PRESSURE / *PRESSURE MEASUREMENT / SCREENS / TIME DEPENDENCE

65. 83A10444
AUTOMATIC PLOTTING OF THE RESULTS OF BENCH TESTS OF TURBINE ENGINES
Automatyzacja graficznego opracowywania wynikow^badan hamownianych silnikow turbinowych
Gorczyca, D.; Krolikowski, R.
Instytut Lotnictwa, Prace, no. 88, 1982, p. 45-53. In Polish. 9 p.

The paper describes a technique for the automatic plotting of the static characteristics of gas turbine engines using values of engine parameters obtained from measurements under stationary conditions. The approach involves the approximation of the static characteristics by polynomials using simplex linear programming; Lagrange interpolation can also be used.

Controlled Terms: APPROXIMATION / *AUTOMATIC TEST EQUIPMENT / *ENGINE TESTS / *GAS TURBINE ENGINES / LINEAR PROGRAMMING / *PLOTTING / STATIC TESTS

66. 82A35078
ICING CONDITIONS ON SEA LEVEL GAS TURBINE ENGINE TEST STANDS
Willcocks, H. J.
AIAA Paper 82-1237; AIAA, SAE, and ASME, Joint Propulsion Conference, 18th, Cleveland, OH, June 21-23, 1982, AIAA 7p. 7 refs.

Engine icing conditions are discussed and various methods of icing prevention are compared. Icing can be caused by a drop in the static temperature within the engine inlet duct or by increase of relative humidity with increasing Mach number till saturation. Two types of icing exist, engine face icing and general stand icing, which includes engine face icing. Stand inlet heaters are found to provide the best solution to engine face and general stand icing, but are not cost-effective to use for icing alone. Engine running appears useful for engine face icing but is hazardous when general stand icing is present. An ice detector rig is described which will discriminate between the two types of icing, and so permit running the engine when appropriate.

Controlled Terms: ANTIICING ADDITIVES / DEICERS / ENGINE INLETS / *ENGINE TESTS / *GAS TURBINE ENGINES / *ICE FORMATION / *ICE PREVENTION / INLET TEMPERATURE / SEA LEVEL / *TEST STANDS

67. 82A35097
LOW CYCLE FATIGUE TESTING FACILITY
Brown, B. T.
AIAA paper 82-1274; AIAA, SAE, and ASME, Joint Propulsion Conference, 18th, Cleveland, OH, June 21-23, 1982, AIAA 9p.

Pratt and Whitney Aircraft has recently completed and validated a unique new testing facility that allows realistic gas turbine core engine cyclic testing with fully instrumented components. This corporate funded Low Cycle Fatigue (LCF) Testing Facility duplicates an engine low pressure compressor or fan, including snap transient characteristics. Low Cycle Fatigue is a major cause of hot section component failure in gas turbine engines but is the least understood. It has been estimated that 50 to 90% of military engine turbine vane replacements are due to LCF. This facility will enable comprehensive investigations to be conducted into LCF and will provide experimental evaluation of advanced engine core components in a cyclic environment to produce a more durable, dependable engine. The facility need, criteria, description, and demonstrated capabilities will be discussed.

Controlled Terms: COMPUTERIZED SIMULATION / CORES / DATA ACQUISITION / *ENGINE TESTS / *FATIGUE TESTS / *GAS TURBINE ENGINES / STRUCTURAL FAILURE / SYSTEMS ENGINEERING / *TEST FACILITIES / TRANSIENT RESPONSE

68. 82A23824
THE APPLICATION OF DYNAMIC COLD NEUTRON FLUOROSCOPY FOR THE VISUALISATION OF FUEL AND OIL SYSTEM OPERATING CHARACTERISTICS IN GAS TURBINE DEVELOPMENT
Stewart, P. A. E.
Aeronautical Journal, vol, 86, Jan. 1982, p. 23-28. 10 refs.

Controlled Terms: *COLD NEUTRONS / ENERGY TECHNOLOGY / *FLOW VISUALIZATION / *FLUOROSCOPY / *FUEL SYSTEMS / *GAS TURBINE ENGINES / *NEUTRON RADIOGRAPHY / NUCLEAR REACTORS / OILS

69. 81N13061
PERFORMANCE EVALUATION OF A PROTOTYPE NONINTERFERENCE TECHNIQUE FOR MEASUREMENT OF TURBINE ENGINES COMPRESSOR BLADE STRESS
Final Report, 1 Oct. 1977 - 1 Jan. 1979
McCarty, P. E.; Thompson, J. W., Jr.
ARO, Inc., Arnold Air Force Station, Tenn.
AD-A090566; AEDC-TR-80-5 Sponsored by AF 23 p.

A noninterference technique for measuring stress in compressor blades of turbine engines is being developed to alleviate disadvantages associated with conventional strain gage measurement systems. The noninterference technique uses blade-tip deflection measurements and special data processing algorithms to infer local blade stress. A prototype of the noninterference technique equipped with a nonintegral blade vibration data processing algorithm has been experimentally validated.

Controlled Terms: ALGORITHMS / BLADE TIPS / *COMPRESSOR BLADES / DATA PROCESSING / ROTOR BLADES (TURBOMACHINERY) / STRAIN GAGES / *STRESS MEASUREMENT / *TURBINE BLADES / *TURBINE ENGINES / *VIBRATION MEASUREMENT

70. 80A42205
A REVIEW OF CURRENT METHODS AND PROBLEMS IN MAKING GAS PATH MEASUREMENTS IN AIRCRAFT GAS TURBINE ENGINES
Alwang, W. G.
ASME Paper 80-GT-75 American Society of Mechanical Engineers, Gas Turbine Conference and Products Show, New Orleans, La., Mar. 10-13, 1980, 6 p. 22 refs.

The gas path of an aircraft gas turbine engine presents some unique measurement problems. As part of the development of an engine, it is necessary to verify all of the critical design parameters such as air and metal temperature, dynamic and steady state stresses, pressure distributions and air flow in order to accurately interpret engine performance and endurance tests. Although a great deal can be accomplished within the current state-of-the-art, some very significant gaps remain in the needed measurement technology, particularly in the hottest sections of the engine. New sensors and measuring techniques are currently under development which promise to overcome many of the current problems.

Controlled Terms: *AIRCRAFT ENGINES / ENGINE DESIGN / ENGINE MONITORING INSTRUMENTS / *ENGINE TESTS / *FLOW MEASUREMENT / *GAS FLOW / *GAS TURBINE ENGINES / MEASURING INSTRUMENTS / PERFORMANCE TESTS / PRESSURE DISTRIBUTION / RELIABILITY ANALYSIS

71. 80N15181.
CLIMATIC CHAMBER TESTING AIRCRAFT, ENGINES ARMAMENT AND AVIONICS; TEST OPERATIONS PROCEDURE - ENVIRONMENTAL TEST CHAMBERS AND FACILITY FOR TESTING AIRCRAFT CONSTRUCTION MATERIALS AND ENGINES
Final Report
Army Test and Evaluation Command, Aberdeen Proving Ground, Md.
AD-A074049; TOP-7-3-521; MTP-7-3-521 Supersedes MTP-7-3-521 35 p.

This document provides information, guidance and methodology for planning and conducting an environmental climatic chamber developmental test of aviation material. Environmental climatic chamber developmental testing in general, determines the degree to which aviation material meets the developmental requirements of the US Army materiel Needs (MN) documents, when subjected to the environmental conditions developed in the climatic chamber.

Controlled Terms: *AIRCRAFT CONSTRUCTION MATERIALS / *AIRCRAFT ENGINES / AIRCRAFT EQUIPMENT / *ENVIRONMENTAL TESTS / HUMAN FACTORS ENGINEERING / PERFORMANCE TESTS / RELIABILITY ENGINEERING / *TEST CHAMBERS / *TEST FACILITIES

72. 80A25447
TRANSPARENT ENGINES AT ROLLS-ROYCE - THE APPLICATION OF HIGH ENERGY X-RAY TECHNOLOGY TO GAS TURBINE DEVELOPMENT
Stewart, P. A. E.
Aircraft Engineering, vol. 52, Feb. 1980, p. 10-13.

Experience with work directed to provide direct viewing of the growths, flexures, or movements in a gas-turbine engine operated in a test facility is reviewed. Prior to the advent of high-energy radiography, the standard practice was to infer information by modifying an engine specially and inserting retractable wearaway probes to measure gas clearances. Alternatively, induction probes were used, but the need to specially prepare an engine still remained. In the mid-1960s, exploratory work with X-rays was conducted, but the X-ray energy level attainable was insufficient. Better results were obtained in 1969 with a flash pulsed high energy X-ray source of about 2.3 million electron volts. The discussion is focused on a successful experiment carried out on the M-45 engine, using iridium 192 and cobalt 60 radioactive isotopes with energy levels ranging from 1 to 2 MeV.

Controlled Terms: DIGITAL TECHNIQUES / *ENGINE TESTING LABORATORIES / FLUOROSCOPY / *GAS TURBINE ENGINES / *IMAGE ENHANCEMENT / IMAGING TECHNIQUES / *RADIOGRAPHY / TEST FACILITIES / X-RAY APPARATUS / *X-RAY INSPECTION

73. 79N27174
THE INTEGRITY OF AIRCRAFT JET ENGINES UNDER THE IMPACT OF FOREIGN BODIES
Integrite des reacteurs d'avions sous impacts de corps etrangers
Hedon, D,; Barrere, J.
Centre d'Essais des Propulseurs, Orsay (France).
In AGARD Stresses, Vibrations, Struct. Integration and Eng. Integrity (Including Aeroelasticity and Flutter) 13 p.

The ingestion of foreign bodies, especially of birds, remains a major hazard to aircraft. The improvement of the resistance of engines to impacts has, for several years, been the object of important efforts on the part of aircraft manufacturers working with official services. The Centre D'Essais des Propulseurs furnished a special installation for this type of research. The experience acquired from tests made show that consideration of impact resistance must be made part of engine design and can influence the general architecture of the project as well as the definition of internal details or of preparations.

Controlled Terms: *AIRCRAFT ENGINES / *BIRD-AIRCRAFT COLLISIONS / DIAPHRAGMS (MECHANICS) / ENGINE DESIGN / *ENGINE FAILURE / GAS GENERATORS / HAIL / *IMPACT RESISTANCE / *INGESTION (ENGINES) / REGULATIONS / RUPTURING / TEST FACILITIES

74. 79A40752
FURTHER TEST RESULTS WITH THE AIRJET DISTORTION GENERATOR - A NEW TOOL FOR AIRCRAFT TURBINE ENGINE TESTING
McIlveen, M. W.
AIAA Paper 79-1185; AIAA, SAE, and ASME, Joint Propulsion Conference, 15th, Las Vegas, Nev., June 18-20, 1979, AIAA 10 p. 6 refs.

An airjet distortion generator system has been developed to produce steady-state total pressure distortion at the inlet of turbine engines. The system employs a method of injecting controlled amounts of high-velocity secondary air counter to the primary airstream to produce a local total pressure decay. Digital computer control provides an on-demand distortion pattern capability. Results of the latest development effort of the ADG are discussed and compared to previous test results in terms of steady-state distortion pattern fidelity, time-variant flow-field characteristics, and engine stability assessment.

Controlled Terms: *ENGINE TESTS / *FLOW DISTORTION / GRAPHS (CHARTS) / *GUIDE VANES / INLET FLOW / *INLET PRESSURE / JET FLOW / *JET IMPINGEMENT / SIMULATORS / TEST EQUIPMENT / TEST FACILITIES / *TURBINE ENGINES / TURBOFAN ENGINES

75. 79A38975
INFRARED SIGNATURE MEASUREMENT TECHNIQUES AND SIMULATION METHODS FOR AIRCRAFT SURVIVABILITY
Varney, G. E.
AIAA Paper 79-1186; AIAA, SAE, and ASME, Joint Propulsion Conference, 15th, Las Vegas, Nev., June 18-20, 1979, AIAA 10 p.

This paper discusses the methodology of relating infrared signatures of aircraft weapon systems to their survivability in a combat situation. Techniques to measure the infrared radiation signatures for gas turbine engines are presented for outdoor static test and wind tunnel model testing. Infrared measurement instrumentation and data analysis methods are given that characterize the band total, spectral and spatial distribution. Techniques for estimating the in-flight aircraft signatures are also presented. Use of these in-flight signatures in air combat simulator for estimating aircraft combat survivability are then discussed.

Controlled Terms: *AIRCRAFT SURVIVABILITY / ENGINE TESTS / FLIGHT TESTS / *GAS TURBINE ENGINES / INFRARED DETECTORS / INFRARED INSTRUMENTS / *INFRARED RADIATION / *INFRARED SPECTROMETERS / RADIATION DISTRIBUTION / *SIGNATURE ANALYSIS / SIMULATORS / STATIC TESTS / WEAPON SYSTEMS / WIND TUNNEL TESTS

76. 78A13018
CINERADIOGRAPHY WITH CONTINUOUS X-RAY SOURCES TO TRACK FLIGHT OF METALLIC FOREIGN OBJECTS IN GAS TURBINES
Huston, A. E.; Stewart, P. A. E.
In: International Congress on High Speed Photography (Photonics), 12th, Toronto, Canada, August 1-7, 1976, Proceedings. (A78-13001 02-35) Bellingham, Wash., Society of Photo-Optical Instrumentation Engineers, 1977, p. 140-145 8 refs. Research supported by the Ministry of Defence.

A requirement for high-speed cineradiographic examination of the flight of metallic foreign objects in gas turbines has led to the development of a cineradiographic system suitable for use with constant-potential X-ray sources. The new system has four elements: (1) a continuous X-ray source, (2) a high-gain X-ray image intensifier tube, (3) a rotating-prism high-speed camera, and (4) a pulse generator. The system has so far been used at speeds up to 10,000 frame/s with exposure times down to 10 microsec. Records have been obtained showing the progress of objects moving at 120 m/s.

Controlled Terms: *CINEMATOGRAPHY / *GAS TURBINES / HIGH SPEED CAMERAS / *HYPERVELOCITY IMPACT / HYPERVELOCITY PROJECTILES / IMAGE INTENSIFIERS / PULSE GENERATORS / *RADIOGRAPHY / *X RAY SOURCES.

77. 77N33196
ACCELERATED MISSION TEST: A VITAL RELIABILITY TOOL
McDonnell, B. J.
Pratt and Whitney Aircraft, West Palm Beach, Fla.
Government Products Div. In AGARD Power Plant Reliability 6 p.

The Accelerated Mission Test (AMT) has been successfully used in the F100 engine programe to anticipate potential future problems. Early identification of service oriented problems has provided the lead time necessary to take corrective action before the problems occur in operation which decreases engine "down" time thereby improving life cycle cost. The AMT is a supplemental testing procedure and must be used in conjunction with all of the advanced structural analysis techniques. Plans are now being developed to conduct accelerated mission tests on engines that have completed the overhaul or depot cycle. The purpose of the testing will be to identify potential problem areas associated with engine parts that have been repaired in accordance with the overhaul procedures.

Controlled Terms: *ACCELERATED LIFE TESTS / AIRCRAFT ENGINES / *ENGINE TESTS / F-100 AIRCRAFT / FIGHTER AIRCRAFT / PERFORMANCE PREDICTION / PERFORMANCE TESTS / *RELIABILITY ANALYSIS / *TURBOFAN ENGINES

78. 77A42000
THE AIRJET DISTORTION GENERATOR SYSTEM - A NEW TOOL FOR AIRCRAFT TURBINE ENGINE TESTING
Overall, B. W.; Harper, R. E.
AIAA Paper 77-993 American Institute of Aeronautics and Astronautics and Society of Automotive Engineers, Propulsion Conference, 13th, Orlando, Fla., July 11-13, 1977, 9 p. 6 refs.

An airjet distortion generator system has been developed to produce stead-state total pressure distortion at the inlet of turbine engines. The system employs a method of injecting controlled amounts of high-velocity secondary air counter to the primary airstream to effect a local total pressure decay. Digital computer control provides an on-demand distortion pattern capability. The AJDG system is described, and the pattern-generating logic is presented. Operational characteristics, turbulence, cycle times, and distortion pattern fidelity are discussed. An engine stability assessment with comparison of stability response to screens and airjet-produced inlet distortion is included.

Controlled Terms: AIR JETS / *AIRCRAFT ENGINES / DIGITAL COMPUTERS / ENGINE INLETS / *ENGINE TESTS / FLOW DISTORTION / *GAS TURBINE ENGINES / PRESSURE DISTRIBUTION / STEADY STATE / *TEST EQUIPMENT

79. 77A41999
SHORT-DURATION TURBINE ENGINE TESTING FOR ENERGY CONSERVATION
Kimzey, W. F.; Wantland, E. C.
AIAA Paper 77-991 American Institute of Aeronautics and Astronautics and Society of Automotive Engineers, Propulsion Conference, 13th, Orlando, Fla., July 11-13, 1977, 12 p.

Development of techniques for obtaining equilibrium (steady-state) performance data from non-equilibrium (transient) turbine engine data to realize test time and energy savings has been accomplished. These techniques have been demonstrated in actual engine tests. Short-duration turbine engine testing (SDTET) involves acquisition of transient turbine engine data and the application of analytically derived corrections to determine equilibrium performance. By this procedure, desired performance data are acquired in approximately one sixth the time normally required by conventional steady-state test techniques. Test instrumentation, data reduction and analysis techniques developed for SDTET, and potential test time savings through applications of SDTET techniques are described.

Controlled Terms: COST REDUCTION / DATA ACQUISITION / *ENERGY CONSERVATION / *ENGINE TESTS / FUEL FLOW / *GAS TURBINE ENGINES / NONEQUILIBRIUM CONDITIONS / OPTIMIZATION / STEADY STATE / TEST FACILITIES / *TESTING TIME

80. 77A41985
SIMULATION OF TURBINE ENGINE OPERATIONAL LOADS
Mulenburg, G. M.; Mitchell, J. G.
AIAA Paper 77-912 American Institute of Aeronautics and Astronautics and Society of Automotive Engineers, Propulsion Conference, 13th, Orlando, Fla., July 11-13, 1977, 10 p 8 refs.

The Arnold Engineering Development Center (AEDC) has been working for four years on the definition and optimization of a new and unique test facility concept which will simulate flight maneuver loads on aircraft propulsion systems. Contributions to the definition of test requirements have come from both the military and civil segments of the propulsion community. This paper is intended as a progress report to interested parties and summarizes the planning and rationale which have led to the proposed facility performance and facility conceptual design. The results of several Air Force and contractor studies are noted and the Turbine Engine Loads Simulator (TELS) is described.

Controlled Terms: AIRCRAFT MANEUVERS / *ENGINE TESTING LABORATORIES / ENVIRONMENT SIMULATION / *FLIGHT SIMULATION / *GAS TURBINE ENGINES / MILITARY AIRCRAFT / OPTIMIZATION / SERVICE LIFE / *TEST FACILITIES

81. 76A37218
EXPERIENCE IN USING HOLOGRAPHIC INTERFEROMETRY FOR INVESTIGATING THE VIBRATION OF ROTOR ELEMENTS IN GAS TURBINE ENGINES
Opyt primeneniia golograficheskoi interferometrii^dlia issledovaniia vibratsii rotornykh elementov^GTD
Bavelskii, D. M.; Trofimovskii, V. V.
Problemy Prochnosti, May 1976, p. 85-87. In Russian.

A technique of holographic interferometry is described for evaluating the vibration resistance of gas turbine rotor elements. The design of the holographic facility for investigating the vibration resistance of blades and disks by a time averaging method is described along with the experimental procedure involved. The proposed technique proves useful in providing an exact picture of the location of vibration nodes and a complete profile of vibration amplitudes for the total deflection of the object tested. It reduces considerably the time necessary for a comprehensive investigation of the characteristic shapes of the vibrations.

Controlled Terms: *ACCELERATED LIFE TESTS / FATIGUE LIFE / FREE VIBRATION / *GAS TURBINE ENGINES / *HOLOGRAPHIC INTERFEROMETRY / LASER APPLICATIONS / NONDESTRUCTIVE TESTS / RELIABILITY ENGINEERING / *ROTOR BLADES / STRESS CONCENTRATION / *STRUCTURAL VIBRATION / *TURBINE WHEELS / WAVE FRONT RECONSTRUCTION

82. 76A14544
INTERNAL RUNNING CLEARANCE MEASUREMENTS IN GAS TURBINES USING HIGH ENERGY X-RADIOGRAPHY
Alwang, W. G.; Kinchen, B.
In: Advances in test measurement. Volume 12 - Proceedings of the Twenty-first International Instrumentation Symposium, Philadelphia, Pa., May 19-21, 1975, p. 339-348. 8 refs.

Controlled Terms: CLARITY / *CLEARANCES / *ENGINE TESTS / FUNCTIONS (MATHEMATICS) / *GAS TURBINE ENGINES / PERFORMANCE TESTS / PHOTOGRAPHIC MEASUREMENT / PHOTOGRAPHIC RECORDING / *RADIOGRAPHY / STEADY STATE / *TEST FACILITIES / TRANSIENT RESPONSE / X-RAY SOURCES

83. 75A46691
ENGINE TESTING USING ADVANCED TECHNIQUES - HIGH ENERGY RADIOGRAPHY OF AIRCRAFT GAS TURBINES
Stewart, P. A. E.
(Institute of Electronic and Radio Engineers, Institution of Electrical Engineers, and Royal Aeronautical Society, Joint Meeting, Bristol University, Bristol, England, Feb. 19, 1975.)
Aeronautical Journal, vol. 79, Aug. 1975, p. 331-343. 13 refs.

Controlled Terms: *AIRCRAFT ENGINES / *ENGINE TESTS / FLUOROSCOPY / *GAS TURBINE ENGINES / PHOTOGRAMMETRY / RADIATION PROTECTION / *RADIOGRAPHY / TELEVISION SYSTEMS / X RAY INSPECTION

84. 75A44559
APPLICATION OF ADVANCED TEST METHODS IN ENGINE DEVELOPMENT
Interavia, vol. 30, Apr. 1975, p. 350-352, 354, 355, 357.

Controlled Terms: *AIRCRAFT ENGINES / COMBUSTION CHAMBERS / COMPRESSOR ROTORS / DISKS (SHAPES) / DYNAMIC LOADS / *ENGINE PARTS / *ENGINE TESTS / FATIGUE TESTS / FLIGHT TESTS / FLOW MEASUREMENT / FUEL SYSTEMS / GAS TURBINES / PERFORMANCE TESTS / STATIC LOADS / TEST EQUIPMENT / TURBINE BLADES

4. INSTRUMENTATION

85. 83A47993
THE IMPACT OF COMPUTERS ON THE TEST CELL OF TOMORROW FOR GAS TURBINE ENGINE TESTS
Ash, C. F.
ASME Paper 83-GT-187 American Society of Mechanical Engineers, International Gas Turbine Conference and Exhibit, 28th, Phoenix, AZ, Mar. 27-31, 1983. 8 p.

The role that computers are to play in engine testing is outlined. It is noted that although the adoption of completely automated closed-loop test cells has been slower than expected, economic pressures and technological advances will combine to make closed-loop testing the standard approach in the years to come. Among the benefits will be better overall management of the engine test program, more consistent and reliable data, more effective use of personnel and equipment, and lower costs. The successful application of a real-time computer system with both open-loop and closed-loop capabilities is discussed. This particular system, the Automatic Data Acquisition and Processing System, managed its first 3000 hours of engine operation without a single hardware or software interruption.

Controlled Terms: COMPUTER PROGRAMS / *COMPUTER TECHNIQUES / DATA ACQUISITION / DATA PROCESSING / *ENGINE TESTS / *FEEDBACK CONTROL / *GAS TURBINE ENGINES / HARDWARE / REAL TIME OPERATION

86. 83A39106
ADVANCED TECHNIQUES FOR MEASUREMENT OF STRAIN AND TEMPERATURE IN A TURBINE ENGINE
Stange, W. A.
AIAA Paper 83-1296; AIAA, SAE, and ASME, Joint Propulsion Conference, 19th, Seattle, WA, June 27-29, 1983. 7 p.

An assessment is made of the following types of instrumentation: dynamic strain sensors, static strain sensors, and metal temperature sensors. Dynamic strain sensors have poor survivability, mainly because of fatigue, erosion, and oxidation. What is more, they cannot be used at temperatures exceeding 1200 F. Two methods under investigation that hold promise for overcoming these limitations and meeting the requirements set by the U.S. Air Force, NASA, and industry are thin-film strain gages and blade tip deflection sensors, both of which are discussed. In discussing static strain sensors, it is pointed out that the current method for measuring static strain is to use wire gages. These, however, cannot normally be used in the hot section of a turbine engine. Alternatives to the wire gage are double core fiber optic strain sensors, thin-film capacitive sensors, and acoustic guided wave sensors. With regard to metal temperature sensors, current practice dictates the use of wire thermocouples. Three alternatives to these are thin-film thermocouples, optical pyrometers, and fiber optic temperature sensors.

Controlled Terms: *ENGINE MONITORING INSTRUMENTS / *ENGINE TESTS / FIBER OPTICS / *GAS TURBINE ENGINES / OPERATING TEMPERATURE / *PYROMETERS /*STRAIN GAGES / STRESS ANALYSIS / TECHNOLOGY ASSESSMENT / THIN FILMS / *TURBINE INSTRUMENTS

87. 83A36327
INSTRUMENTAL PROBLEMS IN SMALL GAS TURBINE ENGINES
Allan, J., III
AIAA Paper 83-1293; AIAA, SAE, and ASME, Joint Propulsion Conference, 19th, Seattle, WA, June 27-29, 1983. 12 p.

The small size, high rotational speeds, and unusual flowpath configurations associated with small gas turbine engine development programs make it necessary to develop instrumentation techniques and systems compatible with the special problems encountered in connection with the smaller engines. Typical measurement techniques include blade tip clearance measurement systems, slip-ring systems, telemetry systems, and torque measurement systems. A description is provided of the 'single-point probe' survey system. This system represents a computer-controlled preprogrammed traversing actuator and data acquisition system which allows vane wake mapping and rotor performance mapping without the use of traditional wake rakes. This method of performance mapping reduces flow blockage and flow disturbances and eliminates measurement inaccuracies associated with sensor-to-sensor variations.

Controlled Terms: ACTUATORS / *ENGINE DESIGN / *ENGINE MONITORING INSTRUMENTS / *GAS TURBINE ENGINES / NUMERICAL CONTROL / PRESSURE DISTRIBUTION / TELEMETRY / TORQUEMETERS / *TURBINE BLADES

88. 83A36326
APPLICATION OF THIN FILM STRAIN GAGES AND THERMOCOUPLES FOR MEASUREMENT ON AIRCRAFT ENGINE PARTS
Stowell, W. R.; Weise, R. A.
AIAA Paper 83-1292; AIAA, SAE, and ASME, Joint Propulsion Conference, 19th, Seattle, WA, June 27-29, 1983. 6 p.

In connection with aerodynamic disturbances caused by wire strain gages on compressor blade air foils, a program was initiated to develop measurement techniques which could provide dynamic strain information from blades in an operating test engine without affecting the response of the blades to their environment and without changing significantly the airflow. Reliable gages could be developed for measurements at temperatures up to 1000 F (540 C). Attention is given to the development of gages which are reliable at metal temperatures of 1200 F (approximately 650 C). Reliable thermocouples for measurements on operating turbine buckets are also being developed. It is intended to apply thin film thermocouples to turbine buckets in connection with a study involving the mapping of temperature profiles in the vicinity of air cooling holes on advanced bucket designs. . Attention is given to a thin film insulator, quality control, and aspects of thin film thermocouple development.

Controlled Terms: *AIRCRAFT ENGINES / ALUMINUM OXIDES / COPPER / *ENGINE TESTS / *GAS TURBINE ENGINES / QUALITY CONTROL / SPUTTERING / *STRAIN GAGES / *THERMOCOUPLES / *THIN FILMS / TITANIUM CARBIDES / TURBINE BLADES

89. 83A36325
ADVANCED TECHNIQUES FOR GAS AND METAL TEMPERATURE MEASUREMENTS IN GAS TURBINE ENGINES
Pinsley, E. A.
AIAA Paper 83-1291; AIAA, SAE, and ASME, Joint Propulsion Conference, 19th, Seattle, WA, June 27-29, 1983. 9 p. 12 refs.

In connection with a continuing improvement regarding the performance of new gas turbine designs, both gas and metal temperature measurements for the next generation of engines will have to be performed at increasingly higher temperature levels in regions where heat fluxes, g-loads, erosion rates, and sensitivity of measurement requirements to instrument installation perturbations will all increase. The present investigation is concerned with the status of a number of advanced techniques for high temperature measurement currently in various stages of development and acceptance. The devices considered for the measurement of metal temperatures include thin film thermocouples, pyrometers, and IR scanning cameras. Approaches for determining gas temperatures are also discussed, taking into account Coherent Anti-Stokes Raman spectroscopy (CARS) and dynamic temperature sensors.

Controlled Terms: *AIRCRAFT ENGINES / *ENGINE PARTS / *GAS TURBINE ENGINES / INFRARED SCANNERS / PYROMETERS / RAMAN SPECTRA / *TEMPERATURE MEASUREMENT / THERMOCOUPLES / THIN FILMS

90. 83A11059
ASTF TEST INSTRUMENTATION SYSTEM DETAIL DESIGN - AEROPROPULSION SYSTEM TEST FACILITY
Rickard, J. R.; Bond, D. C.; Lawley, M. W.
In: ICIASF '81; International Congress on Instrumentation in Aerospace Simulation Facilities, Dayton, OH, September 30, 1981, Record. (A83-11051 01-35) New York, Institute of Electrical and Electronics Engineers, Inc., 1981, p. 61-70. 10 p. 5 refs.

A Test Instrumentation System (TIS) has been designed for the Aeropropulsion System Test Facility (ASTF), now under construction, which will provide a test bed for jet engines of up to 75,000 lb thrust, with a growth capacity to accommodate engines of up to 100,000 lb thrust. The TIS is an integral part of the ASTF which acquires, conditions, processes, records, and displays data from engine tests. Design details are presented for the major hardware groupings of the TIS: the data conditioning system, the wide-band recording system, the static data acquisition and processing system, the dynamic data acquisition and processing system, the mass data storage facility, the executive data-processing system, the display system, and the prime engine parameter subsystem.

Controlled Terms: AIRCRAFT ENGINES / AUTOMATIC TEST EQUIPMENT / DATA ACQUISITION / DATA PROCESSING / DATA RECORDING / DATA SYSTEMS / DISPLAY DEVICES / *ENGINE MONITORING INSTRUMENTS / *ENGINE TESTS / *JET ENGINES / *NETWORK SYNTHESIS / *PROPULSION SYSTEM PERFORMANCE / SYSTEMS ENGINEERING / *TEST FACILITIES

91. 83N29669
TRANSDUCER RELIABILITY IN ENGINEERING RESEARCH AND DEVELOPMENT - JET ENGINE TESTS
Watts, D.
Rolls-Royce Ltd., Derby (England)
PNR-90147; REPRINT-833 820628 19 p.

The failure statistics of 1400 transducers of all types used to measure pressure, flow, vibration and movement are analyzed. Physical damage is the prominent failure factor with 47% of 112 transducers failures. Strain gage statistics are examined separately showing a 9.4% failure rate in 3500 applications. Handling of transducers is shown to be the least well controlled factor. Failures due to over range, contamination, low sensitivity and electronics are also studied.

Controlled Terms: *FAILURE ANALYSIS / FLOW MEASUREMENT / PRESSURE MEASUREMENT / *RELIABILITY ANALYSIS / STRAIN GAGES / TEST FACILITIES / *TRANSDUCERS / TURBOJET ENGINES / VIBRATION METERS

92. 83A25142
NEW INSTRUMENTATION FOR ADVANCED TURBINE RESEARCH
Walters, S.
Mechanical Engineering, vol. 105, Feb. 1983, p. 42-51. 10 p. 11 refs.

Overall performance measurements of jet engines depend on data taken in the compressor, combustor, the inlet, the exit nozzle, the gas path aerodynamic and thermodynamic quantities, and gas path seal clearances. The information gathered comprises the total static pressure, the total temperature, the velocity, and the air angle, as well as the blade tip-to-seal clearance. Pyrometric measurements of the near-IR radiation emitted from airfoils determine the surface temperatures for profiling blade temperature, averaging blade temperatures, and detecting hot blades. A dual spectral pyrometer with Si detectors sensitive to overlapping IR bands is used to control flame temperature to prevent approach to blade melting temperature levels. IR photography developed by NASA permits thermal mapping of stationary blades and definition of accurate relationships between film density and surface temperature. Laser velocimetry allows measurements of local thermal fluid velocity fields, including turbulence, and laser optics can be employed for measuring blade clearance.

Controlled Terms: *ENGINE TESTS / *GAS TURBINE ENGINES / INFRARED PHOTOGRAPHY / LASER ANEMOMETERS / PYROMETERS / ROTOR BLADES (TURBOMACHINERY) / SURFACE TEMPERATURE / *TEMPERATURE MEASUREMENT

93. 83N24829
ANALYSIS OF STRAIN GAGE RELIABILITY IN F-100 JET ENGINE TESTING AT NASA LEWIS RESEARCH CENTER
Holanda, R.
National Aeronautics and Space Administration. Lewis Research Center, Cleveland, Ohio.
NAS 1.15:83325; NASA-TM-83325 12 p.

A reliability analysis was performed on 64 strain gage systems mounted on the 3 rotor stages of the fan of a YF-100 engine. The strain gages were used in a 65 hour fan flutter research program which included about 5 hours of blade flutter. The analysis was part of a reliability improvement program. Eighty-four percent of the strain gages survived the test and performed satisfactorily. A post test analysis determined most failure causes. Five failures were caused by open circuits, three failed gages showed elevated circuit resistance, and one gage circuit was grounded. One failure was undetermined.

Controlled Terms: CIRCUITS / *ENGINE TESTS / FAILURE ANALYSIS / FAN BLADES / FLUTTER ANALYSIS / *JET ENGINES / *RELIABILITY ANALYSIS / *STRAIN GAGES

94. 83A23360
ROTATING STRAIN GAGE INSTRUMENTATION FOR GAS TURBINE ENGINES
Prosser, J. C.
In: Measurements in hostile environments; Proceedings of the International Conference, Edinburgh, Scotland, August 31-September 4, 1981. Newcastle-upon-Tyne, England, British Society for Strain Measurement, 1981. 16 p.

A step-by-step procedure for planning, evaluating, and installing strain gauge instrumentation into gas turbine engines is described. The procedure is divided into six segments: definition of requirements, preliminary installation selection, laboratory testing and evaluation, final installation, test monitor and data evaluation, and teardown analysis. Methods of dealing with the testing problems caused by gauge factor uncertainty, acceleration forces, erosion, gauge and leadwire fatigue, and leadwire attachment restrictions are discussed. Careful adherence to the procedure has resulted in excellent strain gauge durability and measurement uncertainty in the high 'G' and high temperature environment associated with gas turbine engine operation.

Controlled Terms: ACCELERATION (PHYSICS) / ENGINE TESTS / EROSION / FATIGUE LIFE / *GAS TURBINE ENGINES / INSTALLING / *PERFORMANCE TESTS / *ROTATING BODIES / *STRAIN GAGES / *STRESS MEASUREMENT / TEARING / TEMPERATURE EFFECTS

95. 83N13106
INSTRUMENTATION FOR GAS TURBINES
Vleghert, J. P. K.
National Aerospace Lab., Amsterdam (Netherlands).
NLR-MP-81016-U Flight Div. Presented at 4th AGARD Special Course on Flight Test Instrumentation, Delft, Netherlands, May 1981 26 p.

Instrumentation and test techniques for test bed and in flight trouble shooting of performance and handling aspects of gas turbine engines are discussed. Parameters essential for a performance check-up are listed, together with instrumentation systems. Problems such as the choice of sampling location, and the need for absolute integrity for probes in the gas upstream of rotating components are treated. Thrust calibration on a static test bed is considered, together with methods for obtaining in-flight thrust. High-response pressure instrumentation which can detect loss of compressor stall margin is described.

Controlled Terms: CHECKOUT / *ENGINE TESTS / *FLIGHT TEST INSTRUMENTS / FUEL FLOW / GAS TEMPERATURE / *GAS TURBINE ENGINES / PRESSURE MEASUREMENT / ROTATION / *TEST STANDS / THRUST

96. 83A23358
MEASUREMENTS IN HOSTILE ENVIRONMENTS; PROCEEDINGS OF THE INTERNATIONAL CONFERENCE, UNIVERSITY OF EDINBURGH, EDINBURGH, SCOTLAND, AUGUST 31-SEPTEMBER 4, 1981.
Conference sponsored by the British Society for Strain Measurement and Society for Experimental Stress Analysis. Newcastle-upon-Tyne, England, British Society for Strain Measurement, 1981.
445 p.

Strain measurements in hostile environments are discussed. The topics addressed include: strain measuring systems and protections in hostile environments; rotating strain gauge instrumentation for gas turbine engines; creep of rotors under triaxial tension; towards displacement measurements in remote locations by holographic fiberoptic probes; in-plane interferometric strain/displacement measurement at high temperatures; and high temperature thermal strain measurement using laser speckles. Also considered are: high temperature moire interferometry, analysis of grating specification, and development of long-term, short-gauge-length grid structure; strain measurement of acoustically excited aircraft structures at elevated temperature; transient measurements in hostile environments; strain monitoring for the Space Shuttle remote manipulator system; and the influence of environmental effects on the mechanical properties of graphite/epoxy laminates.

Controlled Terms: ACCELERATED LIFE TESTS / ACOUSTIC EXCITATION / *CONFERENCES / DISPLACEMENT MEASUREMENT / ELECTRICAL MEASUREMENT /*ENVIRONMENTAL TESTS / FIBER OPTICS / GAS TURBINE ENGINES / GRAPHITE-EPOXY COMPOSITES / *HIGH TEMPERATURE ENVIRONMENTS / HOLOGRAPHY / METAL-WATER REACTIONS / MOIRE INTERFEROMETRY / PERFORMANCE TESTS / PROTECTIVE COATINGS / QUALITY CONTROL / REMOTE MANIPULATOR SYSTEM / *STRAIN GAGES / *STRESS MEASUREMENT

97. 83N11484
STRAIN GAUGES USED FOR TORQUE MEASUREMENT IN A GAS TURBINE ENVIRONMENT
Chivers, J. W. H.
Rolls-Royce Ltd., Derby (England)
PNR-90111 12 p.

A technique of measuring the torque in the shaft between the low pressure turbine and the fan of the RB211 engine was developed. The low pressure system torque is measured by three independent strain gage bridges, oriented such that they are sensitive to torsional stress in the shaft and insensitive to axial and bending loads. The system was used in three separate engine tests. Absolute system accuracy of better than + or - 1% full scale torque is achieved. Agreement between the bridges is better than + or - 0.2% of mean torque value.

Controlled Terms: CALIBRATING / ENGINE TESTS / ERROR ANALYSIS / *GAS TURBINE ENGINES / *STRAIN GAGES / *TORQUEMETERS / TORSIONAL STRESS / TURBOSHAFTS

98. 83N11485
RADIATION PYROMETRY IN GAS TURBINE RESEARCH AND DEVELOPMENT
Douglas, J.
Rolls-Royce Ltd., Derby (England)
PNR-90116 Electronics and Instrumentation Research Group. 11 p.

Applications of radiation pyrometers to rotating component and turbine blade test rigs, engine testing, and thermography are outlined. They monitor compressor and turbine disk temperatures in high temperature tests. In low pressure testing of turbine blades, the pyrometers ensure that components are not overheated, by controlling the rig cycle. These pyrometers can be used in tests as engine control transducers since pyrometer output can be correlated with gas stream temperature and used to indicate when the engine is at its maximum operating temperature. In thermography, pyrometer systems are used to visualize temperature distributions without the need for absolute temperature measurements.

Controlled Terms: ENGINE TESTS / *GAS TURBINES / HIGH TEMPERATURE TESTS / *RADIATION PYROMETERS / RECORDING INSTRUMENTS / ROTATING DISKS / TEMPERATURE DISTRIBUTION / *TURBINE BLADES / TURBOCOMPRESSORS

99. 82A37005
HIGH TEMPERATURE MEASUREMENT OF GAGE FACTORS
Mina, S.; Roesch, E. R.
In: Society for Experimental Stress Analysis, Spring Meeting, Dearborn, MI, May 31-June 4, 1981, Proceedings. Brookfield Center, CT, Society for Experimental Stress Analysis, 1982, p. 302-307.

Gage factor calibrations of specific strain gage installations are a necessity for an optimization of stress measurement data, especially when tests are conducted in the high temperature environment of a gas turbine engine. Since the gage factor is affected by gage alloy, wire size, gage fabrication and installation technique, and the heat treatment temperature, a knowledge of gage factor variations with temperature is needed for stress data correction at each specific engine test condition. A description is presented of a computerized strain gage facility which is being utilized routinely to calibrate sample batches of high temperature dynamic strain gage installations for specific engine applications at temperatures up to 1700 F. The total system error of the calibration facility is + or - 3%. The automated system represents an improvement over existing standard methods.

Controlled Terms: *CALIBRATING / COMPUTER TECHNIQUES / *ENGINE TESTS / HARDWARE / *HIGH TEMPERATURE ENVIRONMENTS / *STRAIN GAGES / TEMPERATURE PROFILES / WHEATSTONE BRIDGES

100. 82A35476
THE IMPACT OF MICROPROCESSORS ON ROTATING MACHINERY DATA ACQUISITION AND DIAGNOSTIC INFORMATION SYSTEMS
Harker, R. G.; Cronquist, W. E.
ASME Paper 82-GT-319 American Society of Mechanical Engineers, International Gas Turbine Conference and Exhibit, 27th, London, England, Apr. 18-22, 1982, 7 p.

Traditionally, vibration monitoring and protection equipment has been totally separate from the diagnostic and data acquisition equipment as used for rotating machinery information systems. Application oriented utilization of multiple microprocessors in a distributed processing system can virtually eliminate this artificial barrier. The design philosophy, block diagram, and operating results obtained from actual field-installed units will be presented. In addition, its use with a central Host Processor computer based total plant rotating machinery information system will be discussed.

Controlled Terms: ARCHITECTURE (COMPUTERS) / AUTOMATIC TEST EQUIPMENT / *DATA ACQUISITION / DATA RECORDING / DATA REDUCTION / *ENGINE MONITORING INSTRUMENTS / FAIL-SAFE SYSTEMS / FAILURE ANALYSIS / GAS TURBINE ENGINES / *INFORMATION SYSTEMS / MACHINERY / *MICROPROCESSORS / MONITORS / PARALLEL PROCESSING (COMPUTERS) / *ROTATING SHAFTS / *VIBRATION MEASUREMENT

101. 82A35402
ACQUISITION OF F-100/3/ HIGH PRESSURE COMPRESSOR ENTRANCE PROFILES
Rabe, D. C.; Copenhaver, W. W.; Perry, M. S.
ASME Paper 82-GT-215 American Society of Mechanical Engineers, International Gas Turbine Conference and Exhibit, 27th, London, England, Apr. 18-22, 1982, 5 p. 6 refs.

A transportable automatic data acquisition system to obtain high pressure compressor entrance profiles in an F-100 Series 3 gas turbine engine is described. The system was developed, assembled, and tested at Wright-Patterson Air Force Base and transported to a remote location for implementation in a sea level engine test. Acquisition of data was controlled through a Hewlett Packard Model 9825T desktop calculator, preprogrammed to display airflow data in engineering units during the test. Entrance profiles of total and static pressure, temperature, and flow angle for two axial locations are presented. A wedge probe sensing element was positioned at 12 radial locations by remote traversing mechanisms to obtain these profiles. For a total pressure range of 18 to 46 psia (0.13 to 0.32 MPa), acquisition uncertainties in static and total pressure were reduced to below + or - percent of measured values by optimizing data system component uncertainties.

Controlled Terms: AIRBORNE/SPACEBORNE COMPUTERS / *AIRCRAFT ENGINES / CALCULATORS / *DATA ACQUISITION / *ENGINE MONITORING INSTRUMENTS / ENGINE TESTS / *F-100 AIRCRAFT / FLOW DISTRIBUTION / GAS PRESSURE / *GAS TURBINE ENGINES / HEWLETT-PACKARD COMPUTERS / HIGH PRESSURE / *INLET PRESSURE / PRESSURE DISTRIBUTION / PRESSURE MEASUREMENT / STATIC PRESSURE / TEMPERATURE DISTRIBUTION

102. 81A32855
CLOSE COUPLED TELEMETRY FOR OBTAINING LARGE QUANTITIES OF STRAIN AND TEMPERATURE MEASUREMENTS FROM ROTATING COMPONENTS OF A GAS TURBINE ENGINE
Kemp, R. E.
In: International Instrumentation Symposium, 26th, Seattle, Wash., May 5-8, 1980, Proceedings. Part 2. Research Triangle Park, N.C., Instrument Society of America, 1980, p. 505-513.

The application of close coupled telemetry for obtaining large numbers of strain and temperature measurements from the rotating components of a 10,000 horsepower industrial gas turbine engine is discussed. The application given in a prior paper is reviewed, and the improvements made to the telemetry system are described. The methods by which the number of measurements was greatly increased is discussed and some failure data on transmitters is presented.

Controlled Terms: ANTENNAS / *ENGINE TESTS / FAILURE ANALYSIS / *GAS TURBINE ENGINES / *STRAIN GAGES / *TELEMETRY / *TEMPERATURE MEASUREMENT / THERMOCOUPLES / TRANSMITTERS / *TURBINE WHEELS

103. 81N30132
HIGH TEMPERATURE STRAIN GAGE SYSTEM FOR APPLICATION TO TURBINE ENGINE COMPONENTS
Final Report, 15 Jun. 1976 - 15 Aug. 1980
Weise, R. A.; Foster, J. H.
General Electric Co., Cincinnati, Ohio.
AD-A101713; R80AEG388; AFWAL-TR-80-2126 F33615-76-C-2075; AF Proj. 3066 Aircraft Engine Business Group. 253 p.

A three-phase program was completed to develop reliable, high temperature dynamic strain gage systems for application to turbine engine components operating to 1500 F. The strain gage element, intermediate leads and gage fabrication processes that evolved are used over the full temperature range: however, two different application techniques are required to achieve maximum fatigue strength to 1500 F. A composite-ceramic application design is recommended to 700 F. At higher temperatures, the all-FSA or Rokide design is preferred. Gage factor stabilization procedures were established. A strain gage reliability demonstration was conducted on an engine compressor and showed the composite-ceramic gage to have better reliability below 700 F. The report includes a detailed procedure of gage fabrication and application.

Controlled Terms: CERAMICS / COMPOSITE MATERIALS / FABRICATION / *GAS TURBINE ENGINES / RELIABILITY ENGINEERING / *STRAIN GAGES / *THERMAL STRESSES / *TURBOCOMPRESSORS

104. 81A30038
TURBINE PYROMETRY - AN EQUIPMENT MANUFACTURER'S VIEW
Beynon, T. G. R.
ASME Paper 81-GT-136 American Society of Mechanical Engineers, Gas Turbine Conference and Products Show, Houston, Tex., Mar. 9-12, 1981, 7 p.

Optical pyrometry is potentially a valuable technique for temperature measurement and control in gas turbines. However the problems associated with obtaining a clean signal interpretable as a metal temperature can be formidable. The difficulties are examined here in the light of more than 18 years' involvement, by the author's company, with turbine pyrometry. A number of 'ground-rules' are formulated which, it is hoped, will be useful to new and prospective users of the method. Experienced users may find the perspective adopted valuable. Some possibilities arising from recent technical developments are highlighted.

Controlled Terms: *GAS TURBINE ENGINES / METAL SURFACES / MIRRORS / OPTICAL DATA PROCESSING / OPTICAL EQUIPMENT / *OPTICAL PYROMETERS / RESEARCH AND DEVELOPMENT / *TEMPERATURE MEASUREMENT

105. 81A30020
THE USE OF MULTI-CHANNEL RADIO TELEMETERING TECHNIQUES FOR STRESS AND TEMPERATURE MEASUREMENTS IN GAS TURBINE ROTATING COMPONENTS
We-Shung, W.; Wen-Hu, Y.; Wen-Fwu, L.
ASME Paper 81-GT-116 American Society of Mechanical Engineers, Gas Turbine Conference and Products Show, Houston, Tex., Mar. 9-12, 1981, 7 p. 7 refs.

This paper gives a short account of and evaluates a PPM-AM modulation time-division multi-channel telemetry system. With this system it is possible to simultaneously measure seven channels of vibration signals (strain and frequency data) and investigate the phase and strain relationship between the component parts in the blade-disk system coupled vibrations. A description is given of the seven-channel FM modulation time-division multiplex telemetry system for the acquisition of turbine disk static stress field and temperature field data and the operating technique of thermistors and high-temperature strain gauges.

Controlled Terms: BLOCK DIAGRAMS / DATA ACQUISITION / DATA PROCESSING / *ENGINE MONITORING INSTRUMENTS / FREQUENCY MODULATION / *GAS TURBINE ENGINES / MULTICHANNEL COMMUNICATION / *RADIO TELEMETRY / *ROTOR BLADES (TURBOMACHINERY) / STRAIN GAGES / *STRESS MEASUREMENT / STRUCTURAL VIBRATION / *TEMPERATURE MEASUREMENT / THERMISTORS / TIME DIVISION MULTIPLEXING

106. 81A30022
DEVELOPMENT OF THE SELF-TEMPERATURE COMPENSATED RESISTANCE STRAIN GAGE USED UP TO 700 C
Zhi-Qi, Z.; Pei-Qing, H.
ASME Paper 81-GT-118 American Society of Mechanical Engineers, Gas Turbine Conference and Products Show, Houston, Tex., Mar. 9-12, 1981, 7 p.

This paper represents a self-temperature compensated resistance strain gage which is of combined type and developed recently. Because the scatter of the thermal output and the drift of the strain gage are smaller in all heat cycles, they could be compensated by bridge circuit or by dummy gage and better accuracy can be obtained. The gage enables engineers to measure the hot-end parts of aeroengines.

Controlled Terms: AIRCRAFT ENGINES / ALUMINUM ALLOYS / CHROMIUM ALLOYS / DUMMIES / HEAT GENERATION / *HIGH TEMPERATURE TESTS / IRON ALLOYS / PLATINUM ALLOYS / *STRAIN GAGES / *STRESS MEASUREMENT / *TEMPERATURE COMPENSATION / *THERMAL RESISTANCE

107. 81N21114
TELEMETRY: INSTRUMENTATION ON RAPIDLY ROTATING AERO ENGINE PARTS
Riley, P. H.
Rolls-Royce Ltd., Derby (England)
PNR-90038 6 p.

The measurement of both slowly and rapidly changing quantities such as temperature, static and dynamic strain at 27,000 g and elevated temperatures, is discussed. The causes of interference in telemetry of moving parts include phase modulation, transducer wire pickup, amplitude modulation of the received RF signal, and frequency modulation of the transmitter. Techniques for reducing interference are explained. Aluminum bond wires must be used in microcircuits subject to high levels of acceleration. High temperature design considerations for active and passive components include thick film technology, dielectric isolation, and printed ceramic and aluminum capacitors.

Controlled Terms: *AIRCRAFT ENGINES / ELECTROMAGNETIC INTERFERENCE / ENGINE MONITORING INSTRUMENTS / *ENGINE PARTS / HIGH TEMPERATURE / MEASURING INSTRUMENTS / MECHANICAL SHOCK / *RADIO TELEMETRY / *ROTATING BODIES / SHOCK RESISTANCE / STRAIN GAGES / TRANSDUCERS

108. 81N12994
PROBLEM IN THE MEASUREMENT OF METAL TEMPERATURE, GAS TEMPERATURE, GAS TEMPERATURE, GAS TEMPERATURE, HEAT FLUX AND STRAIN IN COMBUSTORS AND TURBINES
Alwang, W. G.
Pratt and Whitney Aircraft Group, East Hartford, Conn.
Commercial Products Div. In AGARD Testing and Meas. Tech. in Heat Transfer and Combust 9 p.

The verification of a gas turbine engine design requires that all critical design parameters be measured as directly and accurately as possible during development testing. The hot section of the engine poses some particularly difficult measurement problems. The limitations of current instrumentation used in the combustor and turbine are described and work in progress to overcome these limitations is reviewed. Among the topics to be covered are: limitations on the use of advanced dual spectral range optical pyrometers for metal surface temperature measurement, use of sputtered thin film thermocouples, problems in measuring gas temperature distributions and burner pattern factor, particularly above 3000 F, problems in measuring static strain and strain range in hot section hardware, and problems in the measurement of radiative and total heat flux.

Controlled Terms: *COMBUSTION CHAMBERS / ENGINE DESIGN / *ENGINE TESTS / GAS TEMPERATURE / *HEAT FLUX / PYROMETERS / *STRAIN RATE / *TEMPERATURE MEASUREMENT / *TURBINES

109. 81N12082
THE DESIGN DEVELOPMENT AND OPERATION OF GAS TURBINE RADIO TELEMETRY SYSTEMS
Worthy, J. G. B.
Rolls-Royce Ltd., Derby (England)
EIR-00733 Presented at ASME 25th Ann. Intern. Gas Turbine Conf., Mar. 1980 9 p.

Measurements made on the rotating components of aero gas turbines are discussed. Radio telemetry systems designed and manufactured with that purpose are reviewed. A summary of operating experience is presented, which includes the problems encountered and the measures taken to overcome them.

Controlled Terms: *AIRCRAFT ENGINES / *DESIGN ANALYSIS / *GAS TURBINES / JET ENGINES / STRAIN GAGES / *STRESS MEASUREMENT / *TELEMETRY / *TEMPERATURE MEASUREMENT / TRANSDUCERS / TURBINE BLADES.

110. 80N17422
FATIGUE STRENGTH TESTING EMPLOYED FOR EVALUATION AND ACCEPTANCE JET-ENGINE INSTRUMENTATION PROBES
Armentrout, E. C.
National Aeronautics and Space Administration. Lewis Research Center, Cleveland, Ohio.
NASA-TM-81402; E-313 Presented at 25th Ann. Intern. Gas Turbine Conf., New Orleans, 9-13 Mar. 1980; sponsored by ASME 25 p.

The fatigue type testing performed on instrumentation rakes and probes intended for use in the air flow passages of jet engines during full scale engine tests is outlined. A discussion of each type of test performed, the results that may be derivod and means of inspection is included.

Controlled Terms: ACCEPTABILITY / *ENGINE MONITORING INSTRUMENTS / FATIGUE LIFE / FATIGUE TESTS / *JET ENGINES / PROBES / *QUALITY CONTROL / RAKES / *RELIABILITY ENGINEERING

111. 80N15133
IMPACT OF NEW INSTRUMENTATION ON ADVANCED TURBINE RESEARCH
Graham, R. W.
National Aeronautics and Space Administration. Lewis Research Center, Cleveland, Ohio.
NASA-TM-79301; E-251 Proposed for presentation at the 1980 Spring Ann. Meeting, New Orleans, 5-13 Mar. 1980; sponsored by ASME 25 p.

A description is presented of an orderly test program that progresses from the simplest stationary geometry to the more complex, three dimensional, rotating turbine stage. The instrumentation requirements for this evolution of testing are described. The heat transfer instrumentation is emphasized. Recent progress made in devising new measurement techniques has greatly improved the development and confirmation of more accurate analytical methods for the prediction of turbine performance and heat transfer. However, there remain challenging requirements for novel measurement techniques that could advance the future research to be done in rotating blade rows of turbomachines.

Controlled Terms: AERODYNAMIC CHARACTERISTICS / COMBUSTION EFFICIENCY / *ENERGY CONSERVATION / FUEL CONSUMPTION / *GAS TURBINE ENGINES / *HEAT TRANSFER / *TEST EQUIPMENT / *TURBOMACHINE BLADES

112. 80N14374
TEMPERATURE AND PRESSURE MEASUREMENT TECHNIQUES FOR AN ADVANCED TURBINE TEST FACILITY
Pollack, F. G.; Cochran, R. P.
National Aeronautics and Space Administration. Lewis Research Center, Cleveland, Ohio.
NASA-TM-79278; E-212 Proposed for presentation at the Intern. Gas Turbine Conf. and Ann. Fluids Engr.Conf., New Orleans, 9-13 Mar. 1980; sponsored by Am. Soc. Mech. Engr. 12 p.

A high pressure, high-temperature turbine test facility constructed for use in turbine cooling research is described. Several recently developed temperature and pressure measuring techniques are used in this facility. The measurement techniques, their status, previous applications and some results are discussed. Noncontact surface temperature measurements are made by optical methods. Radiation pyrometry principles combined with photoelectric scanning are used for rotating components and infrared photography for stationary components. Contact (direct) temperature and pressure measurements on rotating components are expected to be handled with an 80 channel rotary data package which mounts on and rotates with the turbine shaft at speeds up to 17,500 rpm. The data channels are time-division multiplexed and converted to digital words in the data package. A rotary transformer couples power and digital data to and from the shaft.

Controlled Terms: DIGITAL DATA / *GAS TURBINE ENGINES / INFRARED PHOTOGRAPHY / OPTICAL MEASUREMENT / *PRESSURE / PYROMETERS / *ROTATING BODIES / *TEMPERATURE MEASUREMENT / *TEST FACILITIES / TIME DIVISION MULTIPLEXING

113. 80A51917
MEASUREMENT OF BURNT GAS TEMPERATURES BY AN INFRARED RADIATION PYROMETER
Shimizu, S.; Sakai, S.; Wakai, K.; Kikutani, F.
JSME, Bulletin, vol. 23, July 1980, p. 1180-1186. 7 p. 19 refs.

An infrared radiation pyrometer which was used for the measurement of the end gas temperature in an engine has been studied to measure the burnt gas temperature in engines. The theoretical temperature of the pyrometer reading, taking account of the temperature gradients in a measured gas, effects of atmosphere along the pyrometer axis and the spectrum of H2O used as the medium, coincides fairly well with the measured values in the range of 1550-2050 K. The effect of CO2 which has an absorption band in the 2.7 micron H2O band has been examined by both theoretical and experimental means.

Controlled Terms: ABSORPTION SPECTRA / *COMBUSTION PRODUCTS / ENGINE TESTS / *GAS TEMPERATURE / HIGH TEMPERATURE GASES / *INFRARED INSTRUMENTS / *PYROMETERS / *TEMPERATURE MEASUREMENT

114. 80A42156
HIGH-SPEED NONCONTACTING INSTRUMENTATION FOR JET ENGINE TESTING
Scotto, M. J.; Eismeier, M. E.
ASME Paper 80-GT-18 American Society of Mechanical Engineers, Gas Turbine Conference and Products Show, New Orleans, La., Mar. 10-13, 1980, 6 p.

This paper discusses high-speed, noncontacting instrumentation systems for measuring the operating characteristics of jet engines. The discussion includes optical pyrometers for measuring blade surface temperatures, capacitance clearanceometers for measuring blade tip clearance and vibration, and optoelectronic systems for measuring blade flex and torsion. In addition, engine characteristics that mandate the use of such unique instrumentation are pointed out as well as the shortcomings of conventional noncontacting devices. Experimental data taken during engine testing are presented and recommendations for future development discussed.

Controlled Terms: *AUTOMATIC TEST EQUIPMENT / BLADE TIPS / ENGINE MONITORING INSTRUMENTS / *ENGINE TESTS / HIGH SPEED / *JET ENGINES / *OPTICAL PYROMETERS / *PYROMETERS / SURFACE TEMPERATURE / TIME RESPONSE / TURBINE BLADES

115. 80A38934
A NONINTERFERENCE TECHNIQUE FOR MEASUREMENT OF TURBINE ENGINE COMPRESSOR BLADE STRESS
McCarty, P. E.; Thompson, J. W., Jr.; Ballard, R. S.
AIAA Paper 80-1141; AIAA, SAE, and ASME, Joint Propulsion Conference, 16th, Hartford, Conn., June 20-July 2, 1980, AIAA 8 p.

A noninterference technique for measuring stress in compressor blades of turbine engines is being developed to alleviate disadvantages associated with conventional strain-gage measurement systems. The noninterference technique uses blade-tip deflection measurements and special data-processing algorithms to infer local blade stress. A prototype of the noninterference technique equipped with a nonintegral blade vibration data-processing algorithm has been experimentally validated. The validation consisted of comparing the test results of the prototype noninterference system with those of a conventional strain-gage blade stress data system during an aeromechanical test of a turbine engine. Direct comparisons were made of amplitude and spectral results and real-time monitoring capabilities between the prototype noninterference and strain-gage systems for compressor instability and stall conditions. Expansion of the prototype noninterference processing algorithms to include the capability for inferring blade stress from blade vibrations integral to engine speed is planned for the near future. Longer term efforts will identify the necessary criteria for a multistage compressor noninterference stress measurement system for routine support of aeromechanical testing.

Controlled Terms: *COMPRESSOR BLADES / OPTICAL MEASURING INSTRUMENTS / SENSITIVITY / *STRAIN GAGES / *STRESS MEASUREMENT / *TURBINE ENGINES

116. 80A36157
TEMPERATURE AND PRESSURE MEASUREMENT TECHNIQUES FOR AN ADVANCED TURBINE TEST FACILITY
Pollack, F. G.; Cochran, R. P.
National Aeronautics and Space Administration. Lewis Research Center, Cleveland, Ohio.
In: Measurement methods in rotating components of turbomachinery; Proceedings of the Joint Fluids Engineering Gas Turbine Conference and Products Show, New Orleans, La., March 10-13, 1980. New York, American Society of Mechanical Engineers, 1980, p 319-326. 13 refs.

A high pressure, high-temperature turbine test facility is being constructed at the NASA Lewis Research Center for use in turbine cooling research. Several recently developed temperature and pressure measuring techniques will be used in this facility. This paper describes these measurement techniques, their status, previous applications and some results. Noncontact surface temperature measurements will be made by optical methods. Radiation pyrometry principles combined with photoelectric scanning will be used for rotating components and infrared photography for stationary components. Contact (direct) temperature and pressure measurements on rotating components will be handled with an 80-channel rotary data package which mounts on and rotates with the turbine shaft at speeds up to 17,500 rpm. The data channels are time-division multiplexed and converted to digital words in the data package. A rotary transformer couples power and digital data to and from the shaft.

Controlled Terms: COOLING SYSTEMS / DIGITAL TECHNIQUES / *ENGINE TESTS / GAS TURBINE ENGINES / HIGH PRESSURE / HIGH TEMPERATURE TESTS / IMAGE PROCESSING / INFRARED PHOTOGRAPHY / METAL SURFACES / NASA PROGRAMS / *PRESSURE MEASUREMENTS / SURFACE TEMPERATURE / *TEMPERATURE MEASUREMENT / *TEST FACILITIES / THERMAL MAPPING / TIME DIVISION MULTIPLEXING / *TURBINE INSTRUMENTS / *TURBOFAN ENGINES

117. 80A36154
THE DESIGN, DEVELOPMENT AND OPERATION OF GAS TURBINE RADIO TELEMETRY SYSTEMS
Worthy, J. G. B.
In: Measurement methods in rotating components of turbomachinery; Proceedings of the Joint Fluids Engineering Gas Turbine Conference and Products Show, New Orleans, La., March 10-13, 1980. New York, American Society of Mechanical Engineers, 1980, p. 279-287. 8 refs.

The design and operation of gas turbine radio telemetry systems are examined. Measurements on the rotating components of aerogas turbines produce difficult instrumentation problems. This paper describes the Rolls-Royce approach to this problem and the design of over 30 radio telemetry systems manufactured by this company. Constraints on the measuring system, block diagrams of the telemetry system and transducer selection integrated circuit are discussed, and experience using dynamic and strain tests is analyzed. Finally, possible problems such as generation of spurious rotational frequency signals due to poor antenna design and the proximity of stator metal work are considered.

Controlled Terms: AIRCRAFT CONSTRUCTION MATERIALS / *AIRCRAFT DESIGN / *AIRCRAFT ENGINES / FLIGHT TESTS / *GAS TURBINE ENGINES / INTEGRATED CIRCUITS / LOGIC CIRCUITS / *RADIO EQUIPMENT / *ROTATING BODIES / STRAIN GAGES / *TELEMETRY / TEMPERATURE EFFECTS

118. 80A36150
DYNAMIC STRAIN AND TEMPERATURE MEASUREMENT OF AERO-ENGINE TURBINE BLADE
Jimboh, K.; Aono, H.; Hagiwara, Y.
In: Measurement methods in rotating components of turbomachinery; Proceedings of the Joint Fluids Engineering Gas Turbine Conference and Products Show, New Orleans, La., March 10-13, 1980. New York, American Society of Mechanical Engineers, 1980, p. 247-254. 8 refs.

The paper deals with experiments in which free-filament type strain gauges were used to measure the dynamic strains in turbine blades. Using these high-temperature gauges, it proved possible to measure strains in disks and blades at temperatures of 750 C and accelerations of 39,000 g.

Controlled Terms: *DIGITAL TECHNIQUES / *DISPLACEMENT MEASUREMENT / *ENGINE TESTS / HIGH TEMPERATURE TESTS / *STRAIN GAGES / *STRESS MEASUREMENT / STRUCTURAL VIBRATION / TEMPERATURE DISTRIBUTION / *TURBINE BLADES / TURBINE WHEELS

119. 80A31217
THE INVESTIGATION OF TRANSIENT LOADS IN GAS TURBINE ENGINE BLADES USING SPECTRAL ANALYSIS METHODS
Issledovanie peremennykh napriazhenii v lopatkakh^GTD metodami spektral'nogo analiza
Kanunnikov, I. P.; Sidorenko, M. K.
Problemy Prochnosti, Dec. 1979, p. 96-100. In Russian. 5 p.

The feasibility of applying spectral techniques to the analysis of transient loads in gas turbine engine blades is examined. It is shown that the spectrograms of blade stresses obtained with various filters provide frequency data unobtainable by oscillographic methods. The blade model used for spectral analysis, which takes into account low-intensity noise and is based on the theory of random processes, is presented, and it is noted that the model spectra agree well with actual spectra. The interpretation of a stress spectrum is discussed, with attention given to the evaluation of blade damping characteristics, amplitude-frequency characteristics in resonance zones, the intensity of the exciting harmonics, blade eigenfrequencies and the effectiveness of blade modifications. It is concluded that, despite the specialized equipment and amount of time required for the spectral analysis of gas turbine engine blade transient stresses, it represents a valuable source of additional information in tensometry.

Controlled Terms: ENGINE TESTS / *GAS TURBINE ENGINES / *SPECTRUM ANALYSIS / STRAIN GAGES / *STRESS ANALYSIS / TENSOMETERS / *TRANSIENT LOADS / *VIBRATIONAL STRESS

120. 80A22724
APPLICATION OF THE DISCRETE-PHASE METHOD /DPM/ TO THE INVESTIGATION AND MONITORING OF AIRCRAFT TURBINE ENGINE BLADE VIBRATIONS. II
Zastosowanie metody dyskretno-fazowej /MDF/ do^badan i kontroli drgan lopatek lotniczych^silnikow turbinowych. II
Laczkowski, R.
Technika Lotnicza i Astronautyczna, vol. 34, Dec. 1979, p. 10-12. In Polish.

Part I dealt with the ELIA-2 device and its application to the determination of dynamic stresses in spinning blades by measuring the amplitudes of blade tip vibrations. In the present paper, the electromagnetic and capacitance sensors employed in this device are discussed, and a method for calibrating the ELIA-2 device is proposed. The application of the discrete-phase method to the determination of blade resonance vibrations, blade flutter, and blade buffeting is described.

Controlled Terms: *AIRCRAFT ENGINES / CALIBRATING / ELECTROMAGNETS / *ENGINE MONITORING INSTRUMENTS / FLUTTER ANALYSIS / *GAS TURBINE ENGINES / PHASE DEVIATION / RESONANT VIBRATION / SENSORS / STRUCTURAL VIBRATION / *TURBINE BLADES / *VIBRATION MEASUREMENT

121. 80A17730
GAS TURBINE CARCASE AND ACCESSORY VIBRATION - PROBLEMS OF MEASUREMENT AND ANALYSIS
Pearson, D. S.; Holme, A. H. E.; Watts, P. R.
(Society of Environmental Engineers, Symposium on Environmental Engineering Today, London, England, May 9-11, 1979.) Society of Environmental Engineers, Journal, vol. 18-4, Dec. 1979, p. 15-22.

Measuring system requirements, pitfalls in data analysis and severity assessment, and the role of laboratory simulation are presented in terms of gas turbine engine vibration testing. Distortion in piezoelectric accelerometers due to a charge generated by temperature gradients or strain is described, and electrical noise and overload resulting from frequencies of 15 to 10,000 Hz, and peak accelerations from 0.3 to 1000 g during vibrational monitoring, are considered. Spectral analysis is discussed, as are frequency, coherence and transmission path analysis as means of presenting data in visual form, while modal analysis techniques appear capable of visually coordinating previously unrelated engine data. It is suggested that severity criteria be revised to assess 3-plane resolved true motion, the combined effect of simultaneous excitation at a range of frequencies, and the cumulative effect of individual vibration phenomena.

Controlled Terms: ACCESSORIES / ACOUSTIC EXCITATION / *DYNAMIC STRUCTURAL ANALYSIS / ENGINE PARTS / *ENGINE TESTS / *GAS TURBINE ENGINES / GRAPHS (CHARTS) / MECHANICAL DRIVES / SPECTRUM ANALYSIS / STRUCTURAL DESIGN CRITERIA / *STRUCTURAL VIBRATION / TEST EQUIPMENT / *VIBRATION MEASUREMENT

122. 80A12637
A FIBER-OPTIC LINK FOR HIGH-SPEED, DDAS-TO-COMPUTER DATA TRANSMISSION - DIGITAL DATA ACQUISITION SYSTEM FROM RAMJET ENGINE TEST CELL TO BASE CENTRAL DATA PROCESSING CENTER
Mahrenholz, B. G.; Little, R. R., Jr.
In: International Instrumentation Symposium, 25th, Anaheim, Calif., May 7-10, 1979, Proceedings. Part 2. (A80-12601 02-35) Pittsburgh, Pa., Instrument Society of America, 1979, p. 501-512.

This paper describes a fiber-optic data link used to transmit data from a ramjet engine test cell for a distance of two kilometers to a base central data processing center. Over this link, data from a minicomputer-controlled, high-speed, digital data acquisition system are transmitted at rates of up to 690,000 sixteen-bit words a second. The practical problems encountered in the installation of a direct-burial cable to an industrial environment are discussed. A description is given of the equipment used to interface the cable at each end as well as the transmission formats and protocols used in the system.

Controlled Terms: ACOUSTO-OPTICS / *COMMUNICATION CABLES / DATA ACQUISITION / *DATA LINKS / DATA PROCESSING TERMINALS / *DATA TRANSMISSION / *DIGITAL DATA / ENGINE TESTS / *FIBER OPTICS / HIGH SPEED / INSTALLING / MINICOMPUTERS / *OPTICAL COMMUNICATION / OPTICAL DATA PROCESSING / RAMJET ENGINES / TRANSMISSION LINES

123. 80A12630
MEASURING UNSTEADY PRESSURE ON ROTATING COMPRESSOR BLADES WITH SEMICONDUCTOR STRAIN GAGES UNDER GAS TURBINE ENGINE OPERATING CONDITIONS
Englund, D. R.; Grant, H. P.; Lanati, G. A.
National Aeronautics and Space Administration. Lewis Research Center, Cleveland, Ohio.
In: International Instrumentation Symposium, 25th, Anaheim, Calif., May 7-10, 1979, Proceedings. Part 2. Pittsburgh, Pa., Instrument Society of America, 1979, p. 413-426. 7 refs.

The capability for accurate measurement of unsteady pressure on the surface of compressor and fan blades during engine operation was established. Tests were run on miniature semiconductor strain gage pressure transducers mounted in several arrangements. Both surface mountings and recessed flush mountings were tested. Test parameters included mounting arrangement, blade material, temperature, local strain in the blade, acceleration normal to the transducer diaphragm, centripetal acceleration, and pressure. Test results showed no failures of transducers or mountings and indicated an uncertainty of unsteady pressure measurement of approximately + or - 6%, plus 0.1 kPa for a typical application.

Controlled Terms: *AERODYNAMIC STABILITY / *COMPRESSOR BLADES / COMPRESSOR EFFICIENCY / *GAS TURBINE ENGINES / PERFORMANCE TESTS / PRESSURE DISTRIBUTION / *PRESSURE SENSORS / *STRAIN GAGES / TEST EQUIPMENT / *TRANSIENT PRESSURES / TURBOMACHINERY

124. 79N19314
STRAIN GAGE SYSTEM EVALUATION PROGRAM
Final Report
Dolleris, G. W.; Mazur, H. J.; Kokoszka, E., Jr.
Pratt and Whitney Aircraft, East Hartford, Conn.
NASA-CR-159486; PWA-5615-3; NAS3-20298 Commercial Products Div. 126 p.

A program was conducted to determine the reliability of various strain gage systems when applied to rotating compressor blades in an aircraft gas turbine engine. A survey of current technology strain gage systems was conducted to provide a basis for selecting candidate systems for evaluation. Testing and evaluation was conducted in an F 100 engine. Sixty strain gage systems of seven different designs were installed on the first and third stages of an F 100 engine fan. Nineteen strain gage failures occurred during 62 hours of engine operation, for a survival rate of 68 percent. Of the failures, 16 occurred at blade-to-disk leadwire jumps (84 percent), two at a leadwire splice (11 percent), and one at a gage splice (5 percent). Effects of erosion, temperature, G-loading, and stress levels are discussed. Results of a post-test analysis of the individual components of each strain gage system are presented.

Controlled Terms: ACCELERATION (PHYSICS) / *COMPRESSORS / ENGINE TESTS / *GAS TURBINE ENGINES / RELIABILITY ENGINEERING / *ROTOR BLADES (TURBOMACHINERY) / *STRAIN GAGES / *STRESS MEASUREMENT / TEMPERATURE EFFECTS / WEAR TESTS

125. 79A25845
DYNAMIC DATA ANALYSIS GAS TURBINE ENGINE VIBRATION TRANSDUCERS
Pearson, D. S.
Transducer Conference, Wembley, Middx., England, June 26-28, 1978, Paper. 16 p

The requirements for basic dynamic transducers, objectives in their use, and simple logistics of the engine as well as information elements of a gas turbine development process are introduced. Editing techniques are presented by complementary analysis methods through which pre-edited data may be converted selectively into engineering information in a compact and simple form. Four case histories are used to illustrate the techniques, with the first two recording respectively: frequency information derived from several strain gauges during uniform engine acceleration of a blade standard known to fail, and comparative 'g' amplitude data from an accessory gear-box having a major accessory mounted at extremes of an acceptable clamp tightness specification. Cases three and four illustrate respectively: distribution of stress, and an engine mounted accessory used to control the engine throttle.

Controlled Terms: AIRCRAFT ENGINES / *DATA PROCESSING / DYNAMIC TESTS / ENGINE CONTROL / *ENGINE TESTS / *GAS TURBINE ENGINES / STRAIN GAGES / *TRANSDUCERS / *TURBINE INSTRUMENTS / *VIBRATION METERS

126. 79A17600
APPLICATIONS OF ELECTRO-OPTICAL INSTRUMENTATION IN TURBINE ENGINE DEVELOPMENT
Alwang, W. G.
In: International Instrumentation Symposium, 24th, Albuquerque, N. Mex., May 1-5, 1978, Proceedings. Part 1. Pittsburgh, Pa., Instrument Society of America, 1978, p 305-314. 18 refs.

A brief review is presented of the types of electro-optic devices which are available for instrumentation applications, taking into account lasers and light emitting diodes, the use of the photographic process for the detection of light, other photoelectric detectors, fiber optics, modulators, and linear and angular encoders. It is pointed out that fiber optics is extensively used in gas turbine instrumentation work for devices ranging from borescopes to optical pyrometers. Applications of electro-optical instrumentation to turbine engine studies are related to temperature measurement, mechanical measurements, and flow measurement. Optical pyrometers are used for metal temperature measurements, and Raman scattering is employed for gas temperature determinations. Vibration and strain measurements can be performed with the aid of holography, speckle photography, diffraction gratings, optical sensors, reflected laser beams, and optical heterodyning. Attention is also given to clearance and displacement measurements, holographic flow visualization, and laser velocimetry.

Controlled Terms: DISPLACEMENT MEASUREMENT / *ELECTRO-OPTICS / *ENGINE MONITORING INSTRUMENTS / FLOW MEASUREMENT / *GAS TURBINE ENGINES / LASER APPLICATIONS / *OPTICAL MEASURING INSTRUMENTS / PYROMETERS / RAMAN SPECTRA

127. 79A17582
MULTIPLE STRAIN AND TEMPERATURE MEASUREMENTS FROM ROTATING PARTS OF A LARGE INDUSTRIAL GAS TURBINE ENGINE
Kemp, R. E.
In: International Instrumentation Symposium, 24th, Albuquerque, N. Mex., May 1-5, 1978, Proceedings. Part 1. (A79-17576 05-35) Pittsburgh, Pa., Instrument Society of America, 1978, p. 89-102. 10 refs.

The application of close coupled telemetry for obtaining strain and temperature data from rotating components of a large industrial gas turbine engine is described. The selection of telemetry hardware, installation constraints, application techniques and results are discussed. Problems arising from the hardware constraints and installation methods are discussed and application recommendations are made.

Controlled Terms: DATA ACQUISITION / DATA TRANSMISSION / *ENGINE PARTS / FREQUENCY MODULATION / *GAS TURBINE ENGINES / HARDWARE / INDUSTRIAL PLANTS / *RADIO TELEMETRY / *ROTATING BODIES / STRAIN GAGES / *STRESS MEASUREMENT / *TEMPERATURE MEASUREMENT / TRANSMITTER RECEIVERS

128. 79A10805
TURBINE BLADE TIP CLEARANCE MEASUREMENT UTILIZING BORESCOPE PHOTOGRAPHY
Chandler, A. L.; Finkelstein, A. R.
ASME Paper 78-GT-164 American Society of Mechanical Engineers, Gas Turbine Conference and Products Show, London, England, Apr. 9-13, 1978, 10 p.

In this paper, a technique is presented for the determination of turbine rotor blade tip-to-stationary shroud clearance requirements utilizing fiber optics. To accomplish these tip clearance determinations, special rub pins were installed in the turbine shrouds, or tip-shoes, of a 10,000-hp engine. A test procedure was created based upon a transient dimensional analysis, and a cooled borescope and camera were developed. The clearances are presented from a series of successive engine test.

Controlled Terms: *BLADE TIPS / *CLEARANCES / *DIMENSIONAL MEASUREMENT / *ENGINE TESTS / FIBER OPTICS / GAS TURBINE ENGINES / *PHOTOGRAPHIC MEASUREMENT / SHROUDS / TEST FACILITIES / TRANSIENT RESPONSE / *TURBINE BLADES

129. 79A10760
RECENT DEVELOPMENTS IN SENSORS FOR THE GAS TURBINE ENGINE
Baker, P. D.; Masom, R. A.
ASME Paper 78-GT-52 American Society of Mechanical Engineers, Gas Turbine Conference and Products Show, London, England, Apr. 9-13, 1978, 15 p

A review of current technology applied to sensors for the measurement of speed, temperature, and pressure in gas turbine engines. The use of suitable materials and designs to overcome the hostile environments is discussed. The desirability of obtaining a simple interface with control systems is considered.

Controlled Terms: *ENGINE CONTROL / ENGINE MONITORING INSTRUMENTS / GAS TEMPERATURE / *GAS TURBINE ENGINES / *PRESSURE SENSORS / *SPEED INDICATORS / TACHOMETERS / TEMPERATURE MEASUREMENT / *TEMPERATURE SENSORS / *THERMOCOUPLES / TRANSDUCERS

130. 78N13407
RELIABILITY ANALYSIS OF FORTY-FIVE STRAIN-GAGE SYSTEMS MOUNTED ON THE FIRST FAN STAGE OF A YF-100 ENGINE
Holanda, R.; Frause, L. M.
National Aeronautics and Space Administration. Lewis Research Center, Cleveland, Ohio.
NASA-TM-73724; E-9274 20 p.

The reliability of 45 state-of-the-art strain gage systems under full scale engine testing was investigated. The flame spray process was used to install 23 systems on the first fan rotor of a YF-100 engine; the others were epoxy cemented. A total of 56 percent of the systems failed in 11 hours of engine operation. Flame spray system failures were primarily due to high gage resistance, probably caused by high stress levels. Epoxy system failures were principally erosion failures, but only on the concave side of the blade. Lead-wire failures between the blade-to-disk jump and the control room could not be analyzed.

Controlled Terms: ENGINE TESTS / EPOXY RESINS / FAILURE ANALYSIS / *FATIGUE (MATERIALS) / FLAME SPRAYING / FLUTTER ANALYSIS / *JET ENGINES / *RELIABILITY ANALYSIS / ROTOR BLADES (TURBOMACHINERY) / *STRAIN GAGES / *TECHNOLOGY ASSESSMENT

131. 78A37108
A COMPUTER-BASED SYSTEM FOR PROCESSING DYNAMIC DATA FROM AIRCRAFT GAS TURBINE ENGINE STRAIN MEASUREMENTS
Harper, R. E.; Reichenbach, F. M.
ISA Transactions, vol. 17, no. 1, 1978, p. 57-64. AB(United Technologies Corp., Pratt and Whitney Aircraft Group, East Hartford, Conn.) 8 p.

Large numbers of dynamic strain measurements are necessary during aircraft gas turbine development to insure product durability. A new computer based system for the digital processing of dynamic strain data has just entered service at Pratt & Whitney Aircraft. This system features automated handling of calibration and labelling information, and interactive operator communications. Special purpose digital devices are used to increase the throughput rate, to perform FFTs and to provide a high quality hard copy readout. Expansion to handle other dynamic data, including vibration and pressure, is planned.

Controlled Terms: *DATA PROCESSING / *DIGITAL SYSTEMS / DIGITAL TECHNIQUES / *DYNAMIC RESPONSE / *DYNAMIC STRUCTURAL ANALYSIS / DYNAMIC TESTS / ENGINE ANALYZERS / ENGINE TESTS / FAST FOURIER TRANSFORMATIONS / *GAS TURBINE ENGINES / MALFUNCTIONS / *STRAIN GAGES / STRUCTURAL VIBRATION

132. 78A33365
INSTRUMENTATION FOR PROPULSION SYSTEMS DEVELOPMENT
Warshawsky, I.
National Aeronautics and Space Administration. Lewis Research Center, Cleveland, Ohio.
SAE Paper 780076 Society of Automotive Engineers, Congress and Exposition, Detroit, Mich., Feb. 27-Mar. 3, 1978, 11 p. 20 refs.

Various types of instrumentation for the development of propulsion systems are discussed. For the steady-state measurement of local temperature, pressure and flow velocity in gases the devices include: a multielement probe, calibrated thermocouple probes, thermocouple probes designed for low gas velocities, pressure measuring devices for high-speed rotors, and instruments for data pickup from rotating members. For the dynamic measurements of the same factors attention is given to 2-mm diameter pressure transducers, flush-diaphragm transducers, resistance thermometers or thermocouples, and miniature transducers for velocity measurements. Instruments for compressor and turbine-blade instrumentation are described with reference to a pyrometer for mapping turbine-blade surface temperature, a capacitance method for making rotor clearance measurements, and optical detection procedures for blade vibration amplitude.

Controlled Terms: *COMPRESSOR BLADES / *ENGINE TESTS / FLOW DIRECTION INDICATORS / *FLOW MEASUREMENT / GAS TEMPERATURE / *MEASURING INSTRUMENTS / OPTICAL MEASURING INSTRUMENTS / PRESSURE MEASUREMENTS / *PROPULSION SYSTEM PERFORMANCE / PYROMETERS / ROTATING SHAFTS / TEMPERATURE MEASURING INSTRUMENTS / THERMOCOUPLES / *TURBINE INSTRUMENTS / VELOCITY MEASUREMENT

133. 77N31477
LASER VELOCIMETER UTILIZATION IN JET ENGINE ALTITUDE TEST CELLS
Final Report, Oct. 1975 - Jun. 1976
Barnett, D. O.
ARO, Inc., Arnold Air Force Station, Tenn.
AD-A041019; ARO-ETF-TR-76-147; AEDC-TR-77-2; 36 p.

The feasibility of utilizing a laser velocimeter (LV) in turbine engine testing in an altitude test cell was investigated. A one-component LV and associated environmental control system (ECS) were designed, fabricated, and installed in Test Cell J-2 of the Engine Test Facility (ETF). LV measurements made on the centerline of an F101 engine at one axial station downstream of the nozzle exit are presented and compared to the calculated exit velocity. Design data are presented on the vibration levels and temperatures encountered by the LV over a range of engine operating conditions. It was found that sufficient natural seed material existed in the exhaust flow to allow the LV to characterize the exit velocity of a turbojet engine during altitude testing.

Controlled Terms: *ALTITUDE TESTS / DOPPLER EFFECT / *JET ENGINES / *LASERS / TEMPERATURE / TEST FACILITIES / TURBOFAN ENGINES / *VELOCITY MEASUREMENT / VIBRATION

134. 76A37220
A DIGITAL MEASURING SYSTEM FOR THE REGISTRATION OF UNSTEADY TEMPERATURE FIELDS
Tsifrovaia izmeritel'naia sistema dlia^registratsii nestatsionarnykh temperaturnykh^polei
Fot, N. A.; Malyi, A. G.; Kolomiets, IU. A.; Selivanov, M. A.
Problemy Prochnosti, May 1976, p. 92-94. In Russian.

A digital system for registering unsteady temperatures from sensor response during investigations of thermal stress in the elements of aircraft gas turbine engines is described. In the proposed system, transformation of the temperature data into digital code takes place simultaneously with its registration on punched tape. The data is presented in a form suitable to further computer processing with the appropriate algorithms. The system can be used in test stands to study a variety of physico-mechanical and strength properties of material samples and construction elements, or to directly measure temperature fields in full-size objects.

Controlled Terms: *AIRCRAFT ENGINES / ANALOG TO DIGITAL CONVERTERS / BLOCK DIAGRAMS / COMPUTER TECHNIQUES / *DATA RECORDING / *DIGITAL SYSTEMS / *GAS TURBINE ENGINES / *TEMPERATURE DISTRIBUTION / TEST STANDS / *THERMAL STRESSES / THERMOCOUPLES

135. 76A33394
INFRARED PYROMETER FOR HIGH RESOLUTION SURFACE TEMPERATURE MEASUREMENTS ON ROTATING TURBINE BLADES
Uguccini, O.W.
Institute of Electrical and Electronics Engineers and Optical Society of America, Laser and Electro-optical Systems Conference, San Diego, Calif.; May 25-27, 1976, Paper. 19 p.

A high resolution pyrometer was developed and used to obtain temperature profiles of rotating turbine blades at tip speeds up to 366 meters per second (1200 fps). Surface temperature variations from 920 to 1250 K (1200 to 1800 F) can be measured and variations over distances of 0.05 cm (0.020 in.) can be resolved. Temperature profiles were obtained in near real time as hard copies from a computer display terminal. Temperatures measured with the prototype pyrometer and with thermocouples agreed to within 2 percent over the temperature range from 977 to 1144 K (1300 to 1600 F).

Controlled Terms: DISPLAY DEVICES / DYNAMIC RESPONSE / ENGINE TESTS / FIBER OPTICS / GAS TEMPERATURE / *INFRARED DETECTORS / *JET ENGINES / LIGHT EMITTING DIODES / *PYROMETERS / *SURFACE TEMPERATURE / *TEMPERATURE PROFILES / *TURBINE BLADES

136. 75A13248
INFRARED PYROMETER FOR TEMPERATURE MONITORING OF TRAIN WHEELS AND JET ENGINE ROTORS
Wiederhold, P. R.
(American Society for Nondestructive Testing, National Spring Conference, Los Angeles, Calif., Mar. 12-15, 1973.) Materials Evaluation, vol. 32, Nov. 1974. p. 239-243, 248. 5 refs.

Controlled Terms: AIRCRAFT ENGINES / *ENGINE MONITORING INSTRUMENTS / *INFRARED INSTRUMENTS / JET ENGINES / OPTICAL MEASURING INSTRUMENTS / *RADIATION PYROMETERS / RAIL TRANSPORTATION / ROTOR BLADES (TURBOMACHINERY) / *TEMPERATURE MEASUREMENT / *TURBINE BLADES / *VEHICLE WHEELS

137. 75A34658
DATA ACQUISITION AND PROCESSING IN THE NGTE ALTITUDE TEST FACILITY NATIONAL GAS TURBINE ESTABLISHMENT
Dean, G. W.; White, S.W.
ASME Paper 75-GT-124 American Society of Mechanical Engineers, Gas Turbine Conference and Products Show, Houston, Tex., Mar. 2-6, 1975, 13 p.

Controlled Terms: AUTOMATIC TEST EQUIPMENT / *COMPUTER TECHNIQUES / *DATA ACQUSITION / *DATA PROCESSING / DIGITAL SYSTEMS / *ENGINE TESTS / ERROR ANALYSIS / *GAS TURBINE ENGINES / MEASURING INSTRUMENTS / NUMERICAL CONTROL / RELIABILITY ANALYSIS / TEST FACILITIES / TURBOFAN ENGINES

138. 75A34879
A HIGH PERFORMANCE DATA ACQUISITION SYSTEM IN AIRCRAFT JET ENGINE TEST FACILITY
Serlin, O.; McClendon, L.
In: Inventing the model of the future; Proceedings of the Southeast Region 3 Conference, Orlando, Fla., April 29-May 1, 1974. (A75-34851 16-33) New York, Institute of Electrical and Electronics Engineers, Inc., 1974, p. 274, 275.

Controlled Terms: AIRCRAFT ENGINES / *AUTOMATIC TEST EQUIPMENT / COMPUTER PROGRAMS / COMPUTER TECHNIQUES / *DATA ACQUISITION / *DATA SYSTEMS / DISPLAY DEVICES / *ENGINE TESTS / HARDWARE / *JET ENGINES / SYSTEM EFFECTIVENESS / *TEST FACILITIES

139. 75A20433
DYNAMIC CALIBRATION OF PRESSURE SENSORS USED ON ENGINE TEST BEDS
Nadaud, L.; Kuentzmann, P.; Comas, P.
ONERA, TP NO. 1457 La Recherche Aerospatiale, Nov.-Dec. 1974, p. 347-354. 6 refs. In French.

Controlled Terms: *CALIBRATING / DYNAMIC PRESSURE / ENGINE MONITORING INSTRUMENTS / *ENGINE TESTING LABORATORIES / GRAPHS (CHARTS) / *PRESSURE OSCILLATIONS / *PRESSURE SENSORS / *SOLID PROPELLANT ROCKET ENGINES / TEST STANDS / THERMAL PROTECTION / TRANSFER FUNCTIONS

140. 74A28316
A SYSTEMS ENGINEERING APPROACH TO EFFECTIVE ENGINE CONDITION MONITORING
Leiby, D. W.
In: Instrumentation for airbreathing propulsion; Proceedings of the Symposium, Monterey, Calif., September 19-21, 1972. (A74-28283 12-14) Cambridge, Mass., MIT Press, 1974, p. 481-498.

Controlled Terms: *AIRCRAFT ENGINES / DYNAMIC LOADS / *ENGINE MONITORING INSTRUMENTS / *ENGINE TESTS / FOREIGN BODIES / *GAS TURBINE ENGINES / GEAR TEETH / GROUND TESTS / IMPACT DAMAGE / *IN-FLIGHT MONITORING / LUBRICATION SYSTEMS / *SYSTEMS ENGINEERING / TURBOFAN ENGINES / VIBRATION MEASUREMENT

141. 74A28292
ON-THE-SHAFT DATA SYSTEMS FOR ROTATING ENGINE COMPONENTS
Lesco, D. J.; Sturman, J. C.; Nieberding, W. C.
In: Instrumentation for airbreathing propulsion; Proceedings of the Symposium, Monterey, Calif., September 19-21, 1972. (A74-28283 12-14) Cambridge, Mass., MIT Press, 1974, p. 131-140.

Controlled Terms: *DATA SYSTEMS / DATA TRANSMISSION / *DIGITAL SYSTEMS / *ENGINE TESTS / INSTRUMENT ERRORS / MICROELECTRONICS / MULTICHANNEL COMMUNICATION / PRESSURE SENSORS / *ROTATING SHAFTS / *SIGNAL PROCESSING / STRAIN GAGES / STRESS MEASUREMENT / TEMPERATURE MEASUREMENT / TEST FACILITIES / THERMOCOUPLES / *TURBINE ENGINES

142. 74A28283
INSTRUMENTATION FOR AIRBREATHING PROPULSION; PROCEEDINGS OF THE SYMPOSIUM, U.S. NAVAL POSTGRADUATE SCHOOL, MONTEREY, CALIF., SEPTEMBER 19-21, 1972.
Fuhs, A. E.; Kingery, M.
Symposium sponsored by the U.S. Air Force, U.S. Navy, U.S. Army, and NASA Cambridge, Mass., MIT Press (Progress in Astronautics and Aeronautics. Volume 34), 1974. 547 p.

Controlled Terms: *AIR BREATHING ENGINES / AIRCRAFT ENGINES / COMPUTER TECHNIQUES / *CONFERENCES / DATA ACQUISITION / *ENGINE TESTS / FLOW MEASUREMENT / *GROUND TESTS / HOLOGRAPHY / *IN-FLIGHT MONITORING / LASER DOPPLER VELOCIMETERS / *MEASURING INSTRUMENTS / PRESSURE SENSORS / PROPULSION SYSTEM PERFORMANCE / TEMPERATURE SENSORS

143. 73A43743
UTILIZATION OF SEMIARTIFICIAL THERMOCOUPLES IN GAS-TURBINE ENGINE TESTS
Simbirskii, D. F.; Grigor'ev, L. S.; Anikin, A. IA.; Miroshnichenko, L. O.
Aviatsionnaia Tekhnika, vol. 16, no. 2, 1973, p. 148-150. In Russian.

Controlled Terms: CASING / *ENGINE MONITORING INSTRUMENTS / *ENGINE TESTS /*GAS TURBINE ENGINES / HEAT RESISTANT ALLOYS / TEMPERATURE DISTRIBUTION / TEMPERATURE MEASUREMENT / *THERMOCOUPLE PYROMETERS / THERMOELECTRIC MATERIALS / TURBINE BLADES / WIRE

144. 73A42043
TRENDS OF DESIGN IN GAS TURBINE TEMPERATURE SENSING EQUIPMENT
Baas, P. B. R.; Mai, K.
In: Symposium on Temperature, 5th, Washington, D.C., June 21-24, 1971, Proceedings. Part 3. (A73-41976 22-14) Pittsburgh, Instrument Society of America, 1972, p. 1811-1821. 13 refs.

Controlled Terms: *ENGINE MONITORING INSTRUMENTS / ENGINE TESTS / *GAS TEMPERATURE / *GAS TURBINE ENGINES / NOBLE METALS / TEMPERATURE PROBES / *TEMPERATURE SENSORS / THERMAL STABILITY / THERMOCOUPLES / TIME RESPONSE

5. PERFORMANCE EVALUATION

145. 83A35832
THE PREDICTION OF PERFORMANCE OF TURBOJET ENGINE WITH DISTORTED INLET FLOW AND ITS EXPERIMENTAL STUDIES
Qiuting, D.; Mengzi, C.; Huili, S.; Fuqun, C.
In: International Symposium on Air Breathing Engines, 6th, Paris, France, June 6-10, 1983, Symposium Papers (A83-35801 16-07). New York, American Institute of Aeronautics and Astronautics, 1983, p. 258-262. 6 refs.

Controlled Terms: *AIRCRAFT ENGINES / *FLOW DISTORTION / *INLET FLOW / *MATHEMATICAL MODELS / *PERFORMANCE PREDICTION / PRESSURE DISTRIBUTION / RELIABILITY ANALYSIS / STATIC TESTS / TRANSONIC COMPRESSORS / *TURBOJET ENGINES

146. 80N14121
STATIC TEST-STAND PERFORMANCE OF THE YF-102 TURBOFAN ENGINE WITH SEVERAL EXHAUST CONFIGURATIONS FOR THE QUIET SHORT-HAUL RESEARCH AIRCRAFT (QSRA)
McArdle, J. G.; Homyak, L.; Moore, A. S.
National Aeronautics and Space Administration. Lewis Research Center, Cleveland, Ohio.
NASA-TP-1556; E-019 62 p.

The performance of a YF-102 turbofan engine was measured in an outdoor test stand with a bellmouth inlet and seven exhaust-system configurations. The configurations consisted of three separate-flow systems of various fan and core nozzle sizes and four confluent-flow systems of various nozzle sizes and shapes. A computer program provided good estimates of the engine performance and of thrust at maximum rating for each exhaust configuration. The internal performance of two different-shaped core nozzles for confluent-flow configurations was determined to be satisfactory. Pressure and temperature surveys were made with a traversing probe in the exhaust-nozzle flow for some confluent-flow configurations. The survey data at the mixing plane, plus the measured flow rates, were used to calculate the static-pressure variation along the exhaust nozzle length. The computed pressures compared well with experimental wall static-pressure data. External-flow surveys were made, for some confluent-flow configurations, with a large fixed rake at various locations in the exhaust plume.

Controlled Terms: COMPUTER PROGRAMS / *EXHAUST SYSTEMS / FLOW VELOCITY / GRAPHS (CHARTS) / *NOZZLE GEOMETRY / PRESSURE MEASUREMENTS / *QUIET ENGINE PROGRAM / *SHORT HAUL AIRCRAFT / *STATIC FIRING / TABLES (DATA) / TEST STANDS / *TURBOFAN ENGINES

147. 80A27233
INVESTIGATION OF ENGINE PERFORMANCE DEGRADATION OF TF33-P-7 ENGINES
Hart, R. E.
In: Society of Flight Test Engineers, Annual Symposium, 10th, Las Vegas, Nev., September 4-6, 1979. Lancaster, Calif., Society of Flight Test Engineers, 1979. 13 p.

As a result of the actual C-141A cruise performance being less than that in the Flight Manual, the Air Force initiated a test program to attempt to correlate engine performance degradation with time since overhaul. Analysis of test cell data from more than 40 TF33-P-7 engines showed no apparent correlation. In addition, there was no noticeable correlation between performance degradation and engine cycles. These results were unexpected. Test cell calibrations conducted on engines used on the stretch YC-141B flight test program showed no fuel flow or thrust deterioration; however an increase in turbine exhaust temperature was noted. With the current emphasis on fuel economy, further investigation in the area of fuel flow and engine operation time is warranted.

Controlled Terms: *C-141 AIRCRAFT / CALIBRATING / *DATA CORRELATION / DEGRADATION / ENGINE MONITORING INSTRUMENTS / *ENGINE TESTS / *MAINTENANCE / *PERFORMANCE TESTS / *TURBOFAN ENGINES

148. 77A40715
STATISTICAL MODELING OF THE OPTIMAL ADJUSTMENT OF THE PARAMETERS OF A GAS TURBINE ENGINE
Statisticheskoe modelirovanie optimal'noi otladki'parametrov GTD
Meluzov, IU. V.
Aviatsionnaia Tekhnika, vol. 20, no. 1, 1977, p. 83-88. 5 refs. In Russian.

This paper examines digital statistical-simulation of gas turbine engine tests in an investigation of the efficiency of adaptive algorithms of optimal estimation and correction. Particular attention is paid to the identification of the dependence of engine characteristics on regulating elements and to the determination of the number of required corrections of engine characteristics as a function of the amount of a priori information on the distribution of engine parameters.

Controlled Terms: ALGORITHMS / CASCADE FLOW / DENSITY DISTRIBUTION / *DIGITAL SIMULATION / *ENGINE DESIGN / ERROR CORRECTING CODES / *GAS TURBINE ENGINES / STATIC TESTS / *STATISTICAL ANALYSIS

AUTHOR INDEX

REPORT DOCUMENTATION PAGE

1. Recipient's Reference	2. Originator's Reference	3. Further Reference	4. Security Classification of Document
	AGARD-LS-132	ISBN 92-835-0350-3	UNCLASSIFIED

5. Originator Advisory Group for Aerospace Research and Development
North Atlantic Treaty Organization
7 rue Ancelle, 92200 Neuilly sur Seine, France

6. Title
OPERATION AND PERFORMANCE MEASUREMENT ON ENGINES IN SEA LEVEL TEST FACILITIES

7. Presented at a Lecture Series under the sponsorship of the Propulsion and Energetics Panel and the Consultant and Exchange Programme of AGARD on 26–27 April 1984 in Rome, Italy; on 30 April–1 May in Ankara, Turkey and on 3–4 May in Athens, Greece.

8. Author(s)/Editor(s)	9. Date
Various	March 1984

10. Author's/Editor's Address	11. Pages
Various	180

12. Distribution Statement This document is distributed in accordance with AGARD policies and regulations, which are outlined on the Outside Back Covers of all AGARD publications.

13. Keywords/Descriptors

Jet engines
Test facilities
Sea level
Performance tests
Measuring instruments
Data acquisition
Data processing

14. Abstract

This Lecture Series considers all the basic features of turbojets and turbofan testing.

In the introduction, test cell design is set in historical perspective with brief descriptions of the test arrangement and instrumentation used to test the early jet engines. The way in which these have evolved to modern designs is outlined.

Three typical uses for sea-level test beds, routine proof-testing following overhaul, performance evaluation for type certification and general development testing are described and covered in detail by specialist lectures. One lecture is devoted specifically to turboprop testing.

Instrumentation and data handling are dealt with in two lectures, one covering measurement techniques and the other covering data acquisition and handling.

One lecture is devoted to the derivation of the performance of the engine from the test bed measurements.

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